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Search History

DATE: Wednesday, June 12, 2002 Printable Copy Create Case

Set Name side by side	**Query**	**Hit Count**	**Set Name** result set
	DB=USPT,PGPB,JPAB,EPAB,DWPI,TDBD; PLUR=YES; OP=ADJ		
L18	L17 and l8	1	L18
L17	L16 and (current)	2	L17
L16	L15 and (phase or portion or path)	2	L16
L15	L14 and (first or second or third or fourth or one or two or three or four)	2	L15
L14	L13 and (magnitude or amplitude or intensity)	2	L14
L13	L12 and (parallel or series)	3	L13
L12	L11 and (bias or value or threshold$4)	3	L12
L11	L10 and (sequence)	3	L11
L10	L9 and (transistor)	5	L10
L9	L7 and (diode or antiparallel or anti-parallel or back-to-back or "back to back")	9	L9
L8	L7 and (SCR or (silicon with controlled with rectifier))	1	L8
L7	L6 and (pulse)	70	L7
L6	L5 and (conduct$6)	71	L6
L5	L4 and (switch$6)	189	L5
L4	L3 and (gradient with amplifier with assembly)	286	L4
L3	L2 and (gradient with (amplifier or assembly or coil))	4767	L3
L2	L1 and (gradient)	23027	L2
L1	((magnetic adj resonance) or MRI or NMR)	130020	L1

END OF SEARCH HISTORY

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Search Results - Record(s) 1 through 9 of 9 returned.

☐ 1. Document ID: US 6034565 A

L9: Entry 1 of 9 File: USPT Mar 7, 2000

US-PAT-NO: 6034565
DOCUMENT-IDENTIFIER: US 6034565 A

TITLE: Power amplifier for use in an NMR tomography apparatus

DATE-ISSUED: March 7, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Schweighofer; Peter	Nuremberg			DEX

US-CL-CURRENT: 330/10; 330/251

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 2. Document ID: US 6031422 A

L9: Entry 2 of 9 File: USPT Feb 29, 2000

US-PAT-NO: 6031422
DOCUMENT-IDENTIFIER: US 6031422 A

TITLE: Power amplifier and nuclear magnetic resonance tomography apparatus employing same

DATE-ISSUED: February 29, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Ideler; Karl-Heinz	Spardorf			DEX

US-CL-CURRENT: 330/10; 324/322

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 3. Document ID: US 6028476 A

L9: Entry 3 of 9 File: USPT Feb 22, 2000

US-PAT-NO: 6028476

DOCUMENT-IDENTIFIER: US 6028476 A

TITLE: Power switched amplifer

DATE-ISSUED: February 22, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Schweighofer; Peter	Nuremberg			DEX

US-CL-CURRENT: 330/10; 330/251

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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4. Document ID: US 5680047 A

L9: Entry 4 of 9 File: USPT Oct 21, 1997

US-PAT-NO: 5680047
DOCUMENT-IDENTIFIER: US 5680047 A

TITLE: Multipl-tuned radio frequency coil for simultaneous magnetic resonance imaging and spectroscopy

DATE-ISSUED: October 21, 1997

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Srinivasan; Ravi	Richmond Hts	OH		
Liu; Haiying	Euclid	OH		
Elek; Robert A.	Chardon	OH		

US-CL-CURRENT: 324/318; 600/422

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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5. Document ID: US 5500596 A

L9: Entry 5 of 9 File: USPT Mar 19, 1996

US-PAT-NO: 5500596
DOCUMENT-IDENTIFIER: US 5500596 A

TITLE: Local coil array for magnetic resonance imaging of the lower extremities

DATE-ISSUED: March 19, 1996

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Grist; Thomas M.	Madison	WI		
Alley; Marcus T.	Madison	WI		

US-CL-CURRENT: 324/318; 324/322, 600/422

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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6. Document ID: US 5270657 A

L9: Entry 6 of 9 File: USPT Dec 14, 1993

US-PAT-NO: 5270657
DOCUMENT-IDENTIFIER: US 5270657 A

TITLE: Split gradient amplifier for an MRI system

DATE-ISSUED: December 14, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Wirth; William F.	Sullivan	WI		
McFarland; Thomas G.	Hartland	WI		
Vavrek; Robert M.	Waukesha	WI		
Roemer; Peter B.	Schenectady	NY		
Mueller; Otward M.	Ballston Lake	NY		
Park; John N.	Rexford	NY		

US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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7. Document ID: US 5243287 A

L9: Entry 7 of 9 File: USPT Sep 7, 1993

US-PAT-NO: 5243287
DOCUMENT-IDENTIFIER: US 5243287 A

TITLE: Dynamically detuned NMR field coil

DATE-ISSUED: September 7, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Hashoian; Ralph S.	Brookfield	WI		
Prost; Robert W.	Nashotah	WI		
Frederick; Perry S.	Waukesha	WI		

US-CL-CURRENT: 324/318; 324/322

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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8. Document ID: US 5162738 A

L9: Entry 8 of 9 File: USPT Nov 10, 1992

US-PAT-NO: 5162738
DOCUMENT-IDENTIFIER: US 5162738 A

TITLE: Coil and coupling arrangement

DATE-ISSUED: November 10, 1992

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Sepponen; Raimo	Helsinki			FIX

US-CL-CURRENT: 324/318; 324/322

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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9. Document ID: US 4820986 A

L9: Entry 9 of 9 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Mansfield; Peter	Beeston			GBX
Coxon; Ronald J.	Wollaton			GBX

US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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Term	Documents
DIODE.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	391651
DIODES.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	195912
ANTIPARALLEL.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	6702
ANTIPARALLELS	0
ANTI-PARALLEL.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	5735
ANTI-PARALLELS.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	1
BACK-TO-BACK.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	15762
BACK-TO-BACKS	0
"BACK TO BACK".DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	0
(7 AND (ANTI-PARALLEL OR ANTIPARALLEL OR BACK-TO-BACK OR "BACK TO BACK" OR DIODE)).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	9
(L7 AND (DIODE OR ANTIPARALLEL OR ANTI-PARALLEL OR BACK-TO-BACK OR "BACK TO BACK")).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	9

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Previous Page Next Page

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☐ 1. Document ID: US 6034565 A

L10: Entry 1 of 5 File: USPT Mar 7, 2000

US-PAT-NO: 6034565
DOCUMENT-IDENTIFIER: US 6034565 A

TITLE: Power amplifier for use in an NMR tomography apparatus

DATE-ISSUED: March 7, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Schweighofer; Peter	Nuremberg			DEX

US-CL-CURRENT: 330/10; 330/251

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 2. Document ID: US 6031422 A

L10: Entry 2 of 5 File: USPT Feb 29, 2000

US-PAT-NO: 6031422
DOCUMENT-IDENTIFIER: US 6031422 A

TITLE: Power amplifier and nuclear magnetic resonance tomography apparatus employing same

DATE-ISSUED: February 29, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Ideler; Karl-Heinz	Spardorf			DEX

US-CL-CURRENT: 330/10; 324/322

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 3. Document ID: US 6028476 A

L10: Entry 3 of 5 File: USPT Feb 22, 2000

US-PAT-NO: 6028476

DOCUMENT-IDENTIFIER: US 6028476 A

TITLE: Power switched amplifer

DATE-ISSUED: February 22, 2000

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Schweighofer; Peter	Nuremberg			DEX

US-CL-CURRENT: 330/10; 330/251

☐ 4. Document ID: US 5270657 A

L10: Entry 4 of 5 File: USPT Dec 14, 1993

US-PAT-NO: 5270657
DOCUMENT-IDENTIFIER: US 5270657 A

TITLE: Split gradient amplifier for an MRI system

DATE-ISSUED: December 14, 1993

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Wirth; William F.	Sullivan	WI		
McFarland; Thomas G.	Hartland	WI		
Vavrek; Robert M.	Waukesha	WI		
Roemer; Peter B.	Schenectady	NY		
Mueller; Otward M.	Ballston Lake	NY		
Park; John N.	Rexford	NY		

US-CL-CURRENT: 324/322; 324/318

☐ 5. Document ID: US 4820986 A

L10: Entry 5 of 5 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
Mansfield; Peter	Beeston			GBX
Coxon; Ronald J.	Wollaton			GBX

US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC

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Term	Documents
TRANSISTOR.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	506280
TRANSISTORS.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	275115
(9 AND TRANSISTOR).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	5
(L9 AND (TRANSISTOR)).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	5

Display Format: - | Change Format

Previous Page   Next Page

L10: Entry 2 of 5 File: USPT Feb 29, 2000

DOCUMENT-IDENTIFIER: US 6031422 A
TITLE: Power amplifier and nuclear magnetic resonance tomography apparatus employing same

Abstract Paragraph Left (1):
A power amplifier has a supply assembly for offering an intermediate circuit voltage and an output stage connected to the supply assembly for generating an output voltage from the intermediate circuit voltage. The supply assembly contains at least two voltage sources that can be optionally connected in parallel or in series via at least one switch stage. A nuclear magnetic resonance tomography apparatus can be equipped with such a power amplifier. The power amplifier exhibits the required high performance capability in quantitative and qualitative terms, with low losses.

Brief Summary Paragraph Right (2):
The invention is directed to a power amplifier and to a nuclear magnetic resonance tomography apparatus employing same. The power amplifier can be utilized in all fields wherein high output voltages and currents must be offered, particularly for inductive loads. For example, the amplifier is suitable for driving motors and actuators in automation technology, traffic technology and systems technology. In particular, however, the amplifier is suitable for use in medical technology as a gradient amplifier in nuclear magnetic resonance tomography (magnetic resonance imaging).

Brief Summary Paragraph Right (4):
A nuclear magnetic resonance tomography apparatus typically has an orthogonal gradient coil system that surrounds the patient volume. A gradient amplifier which supplies the coil with an exactly regulated current is provided for each gradient coil. For example, the current through each gradient coil can reach values up to 300 A in a predetermined current curve that must be adhered to with a precision in the mA range. In order to achieve the steep current edges that are also required, voltages of, for example, over 1000 V must, for example, be applied to the gradient coil. The precision and dynamics of the gradient current are critical for the image quality. Moreover, the gradient amplifier must offer adequate power in order to accommodate the ohmic losses given a constant current flow of, for example, 300 A through the gradient coil, even in the case of longer current pulses.

Brief Summary Paragraph Right (5):
U.S. Pat. No. 5,515,002 discloses a gradient amplifier having a supply assembly for offering a intermediate circuit voltage and an output stage connected to the supply assembly for generating an output voltage from the intermediate circuit voltage. The output stage is fashioned as a switched output stage employing bridge circuitry, with MOSFET transistors being utilized as switch elements.

Brief Summary Paragraph Right (6):
The intermediate circuit voltage in this known gradient amplifier must be correspondingly high because of the high output voltages to be achieved for fast current variations. Further, a high switching frequency is required in order to achieve the required current regulating precision given slight residual ripple. For these reasons, high switching losses occur at the MOSFET transistors of the output stage.

Brief Summary Paragraph Right (8):
The above object is achieved in accordance with the principles of the present invention in a power amplifier, particularly a gradient amplifier for use in a nuclear magnetic resonance tomography apparatus, having a supply assembly which

produces an intermediate circuit voltage, an output stage connected to the supply assembly which generates an output voltage from the intermediate circuit voltage, and wherein the supply assembly contains at least two voltage sources which can be selectively connected in parallel or in series via at least one switch stage.

Brief Summary Paragraph Right (9):
Because at least two voltage sources of the supply assembly are optionally switchable parallel or in series, the intermediate circuit voltage can be matched to the output voltage of the amplifier which is to be achieved. Given high current rise rates, there is the possibility of temporarily offering a correspondingly high intermediate circuit voltage by a series connection of the voltage sources. When, by contrast, a lower output voltage is required (possibly given a high current intensity), the voltage sources can be connected in parallel. A higher on/off ratio (duty cycle) of the switch elements of the output stage is possible as a result of the lower intermediate circuit voltage achieved in this way, so that significantly lower switching losses occur. Moreover, the required power is uniformly divided among the voltage sources, so that high continuous powers are possible. Overall, the inventive gradient amplifier thus exhibits considerable advantages with respect to dissipated power, cooling requirements, structural size and costs.

Brief Summary Paragraph Right (10):
In a preferred embodiment, the supply assembly of the power amplifier is formed of a number of branches connected in parallel. In each branch one of the voltage sources is connected in series with at least one diode. Each switch is preferably connected to opposite poles of two voltage sources. The voltage sources are preferably connected in series when the switch is conductive (in the momentary direction of the current) but are otherwise connected in parallel.

Brief Summary Paragraph Right (12):
In the feedback mode of the power amplifier, the magnetic energy stored in the inductive load can be returned to the power amplifier via unbiased diodes. The voltage sources are preferably connected in series for faster current dismantling. This can ensue by including one diode in each switch arrangement. Alternatively or additionally, each switch arrangement can be actively driven in a feedback mode in order to connect the voltage sources in series. The combination of these two possibilities has the advantage that transition problems are avoided given a reversal of the current direction due to an activation of the switch arrangement at the zero-axis crossing. In preferred embodiments, the recognition of the onset of the feedback mode ensues with an evaluation of the current curve or by direct measurement at the switch devices.

Brief Summary Paragraph Right (13):
In the normal mode of the power amplifier, the voltage sources are preferably connected in series when the output voltage to be achieved exceeds a predetermined threshold, and thus a high intermediate circuit voltage is required. Other switching strategies are also possible, particularly those wherein a future current requirement or a charge condition of the individual voltage sources is taken into consideration.

Brief Summary Paragraph Right (14):
The output stage preferably includes a switch bridge and generates the output voltage with pulse-width modulation.

Detailed Description Paragraph Right (1):
The supply assembly 10 shown in FIG. 1 includes a first voltage source 12 for offering a first supply voltage U.sub.1, a second voltage source 14 for offering a second supply voltage U.sub.2, a first diode 16, a second diode 18 and a switch stage 20. In the exemplary embodiment described here, the voltages U.sub.1 and U.sub.2 are equal.

Detailed Description Paragraph Right (2):
A first branch of the supply assembly 10 is formed by the first voltage source 12 and the first diode 16, whose anode is connected to the positive pole of the first voltage source 12. Together, the second voltage source 14 and the second diode 18, which has its cathode connected to the negative pole of the second voltage source 14, form a second branch of the supply assembly 10. The two branches are connected in parallel and are connected to two intermediate circuit terminals 26. An intermediate circuit voltage U.sub.z generated by the supply assembly 10 is across terminals 26.

Detailed Description Paragraph Right (3):
The switch stage 20 is formed of a MOSFET transistor 22 with an inherent diode 24 and is connected between the two branches, to the positive pole of the first voltage source 12 and the negative pole of the second voltage source 14. MOSFET modules suitable for the switch stage 20 are available, for example, under the model designation "Siemens BSM". The cathode of the inherent diode 24 is connected to the positive pole of the first voltage source 12 and the anode is connected to the negative pole of the second voltage source 14. A control terminal (gate terminal) of the switch stage 20 is connected to a control unit 28.

Detailed Description Paragraph Right (4):
FIG. 2 shows a known output stage 30 that is connected to the supply assembly 20 via the intermediate circuit terminals 26. The output stage 30 is fashioned on the basis of bridge circuitry with four bridge arms. The bridge arms respectively contain a switch element 32-38 and diodes 40-46, with each switch element 32-38 connected in series with the respective diode 40-46 in the same bridge arm. The switch elements 32-38 are MOSFET transistors that each contain an inherent diode. The four bridge arms are arranged in parallel and are connected to the intermediate circuit voltage U.sub.Z. The switch elements 32-38 are driven by the control unit 28, that includes a current regulator and pulse-width modulator.

Detailed Description Paragraph Right (5):
Respective inductors 48-54 are connected to the junctions of the series-connected switch elements 32-38 and diodes 40-46. The inductors 48-54 are arranged in two pairs, with the inductors in each pair connected in series. The junction between each inductor pair is connected to one of the output terminals 56. A predominantly inductive load 58, a gradient coil here, is connected to the two output terminals 56. An output voltage U.sub.A of the output stage 30 is across the load 58, and an output current I.sub.A flows through the load 58. The functioning of the output stage 30 and its structure are disclosed in greater detail in German OS 40 07 566 (corresponding to U.S. Pat. No. 5,113,145), the latter of which is incorporated herein by reference.

Detailed Description Paragraph Right (6):
All components of the gradient amplifier are wired by low-inductance circuit boards with planar conductor structures in order to avoid parasitic voltage spikes, as described in German OS 40 07 566 and U.S. Pat. No. 5,113,145.

Detailed Description Paragraph Right (7):
During operation of the gradient amplifier shown in FIG. 1 and FIG. 2, the control unit 28 drives the switch stage 20 of the supply assembly 10 and the switch elements 32-38 of the output stage 30. When the switch stage 20 (either the MOSFET transistor 22 or the inherent diode 24) is conducting, the voltage sources 12 and 14 are connected in series. When, by contrast, the switch stage 20 is open (non-conducting), then the voltage sources 12 and 14 deliver the intermediate circuit voltage U.sub.Z in parallel circuitry.

Detailed Description Paragraph Right (8):
The control unit 28 determines the required output voltage U.sub.A as well as the operating condition (normal or feedback mode) of the power amplifier and switches the MOSFET transistor 22 into a conductive state when either the output voltage U.sub.A exceeds a predetermined threshold or a feedback mode occurs. Further, the control unit 28 drives the switch elements 32-38 of the output stage 30 in order to generate the output current I.sub.A corresponding exactly to a reference current value by pulse-width modulation.

Detailed Description Paragraph Right (11):
The high current rise rate in the time span t.sub.1 -t.sub.2 that requires a high output voltage U.sub.A exceeds the threshold prescribed in the control unit 28, so that the MOSFET transistor 22 is placed in its conducting state, and the voltage sources 12 and 14 are thus connected in series. The voltage U.sub.1 +U.sub.2 (or 2.multidot.U.sub.1 because U.sub.1 is equal to U.sub.2) is now across the terminals 26 as the intermediate circuit voltage U.sub.Z. The output voltage U.sub.A can be regulated up to the full intermediate circuit voltage U.sub.Z.

Detailed Description Paragraph Right (12):
If, deviating from FIG. 3, only a gradual rise of the output voltage U.sub.A is required, the control unit 28 likewise doubles the intermediate circuit voltage

U.sub.Z as soon as the threshold is exceeded. The voltage discontinuity of the intermediate circuit voltage U.sub.Z is immediately compensated by a corresponding drive of the switch elements 32-38 of the output stage 30 (reducing the active pulse widths), so that a linear regulation, without any discontinuities of the output voltage U.sub.A and of the output current I.sub.A is assured.

Detailed Description Paragraph Right (13):
When the current rise rate falls below the threshold in terms of magnitude, or when (in the time span t.sub.2 -t.sub.3 in FIG. 3) the current reaches the pulse maximum, then the control unit 28 places the MOSFET transistor 22 in a blocking state. Via the diodes 16 and 18 acting as decoupling diodes, the voltage sources 12 and 14 are thus switched into the parallel mode. The intermediate circuit voltage drops to U.sub.Z =U.sub.1 =U.sub.2, resulting in significantly lower switching losses at the switch elements of the output stage 30, and the power required for the compensation of the ohmic losses in the load 58 is uniformly distributed between the voltage sources 12 and 14.

Detailed Description Paragraph Right (14):
The inductive load 58 is rapidly demagnetized (negative current ramp di/dt) in the time span t.sub.3 -t.sub.4. The magnetic energy (1/2.multidot.L.multidot.I.sub.A.sup.2) stored in the load 58 is thereby fed back into the voltage sources 12 and 14. A high intermediate circuit voltage U.sub.Z is again required for rapidly dismantling the output current I.sub.A in this feedback mode. Even without the intervention of the control unit 28, the voltage sources 12 and 14 are connected in series here because the diodes 16 and 18 are blocking in the feedback path and the inherent diode 24 of the switch means 20 is conductive. Regardless of the amplitude of the intermediate circuit voltage U.sub.Z, a continuous current regulation by pulse-width modulation of the output stage 30 also ensues.

Detailed Description Paragraph Right (16):
A negative output current I.sub.A is built up in the load 58 beginning at the point in time t.sub.5. Since the polarity of the output current I.sub.A is defined in a known way by the drive of the switch bridge in the output stage 30 (and the intermediate circuit voltage U.sub.Z always exhibits a constant polarity), the switch unit 20 is driven here in the same way that was set forth above for a positive output current I.sub.A.

Detailed Description Paragraph Right (17):
As presented above, the inherent diode 24 is in a conducting stage in the feedback mode, so that an additional drive of the MOSFET transistor 22 is actually not required. If, however, a direct change from one direction of the output current I.sub.A to the other direction is to ensue, the MOSFET transistor 22 must be switched to the conducting state no later than the zero-axis crossing. If cut-in took place exactly at the zero-axis crossing, however, this would be time-critical and could lead to undesired noise pulses. The control unit 28 therefore always places the MOSFET transistor 22 into a conductive state when a voltage in the conducting direction is across the inherent diode 24. This avoids the problem just described and is possible without further difficulty since the drain-source channel of the MOSFET transistor 22 is conductive in both directions.

Detailed Description Paragraph Right (18):
An alternative embodiment of the supply assembly 10 shown in FIG. 4 is expanded by a third branch compared to that shown in FIG. 1. This third branch includes a third voltage source 14' for offering a third supply voltage U.sub.3, with U.sub.1 =U.sub.2 =U.sub.3. The third voltage source 14' is connected to the intermediate circuit terminals 26 via a further diode 18'. An additional diode 16' is connected as a decoupling diode between the positive pole of the second voltage source 14 and the corresponding intermediate circuit terminal 26.

Detailed Description Paragraph Right (19):
Like the switch stage 20, a further switch stage 20' is composed of a MOSFET transistor 22' with an inherent diode 24' and is connected between the second and the third branches of the supply assembly 10, to the positive pole of the second voltage source 14 and to the negative pole of the third voltage source 14'. A control input of the switch stage 20' is connected to the control means 28.

Detailed Description Paragraph Right (20):
During operation of a gradient amplifier that contains the supply assembly 10 of

FIG. 4 and the output stage 30 of FIG. 2, the two switch stages 20 and 20' in the exemplary embodiment described here are always driven in common. When the switch stages 20 and 20' are conducting, then the voltage sources 12, 14 and 14' are connected in series. The intermediate circuit voltage U.sub.Z thus amounts to U.sub.1 +U.sub.2 +U.sub.3 or, since the voltages U.sub.1 through U.sub.3 are the same, three times the value of any of these voltages. When the switch stages 20 and 20' are open (non-conducting), then the voltage sources 12, 14 and 14' act in parallel and U.sub.Z =U.sub.1 =U.sub.2 =U.sub.3 applies. A variation of the intermediate circuit voltage by a factor of 3 is thus possible overall given the circuit of FIG. 4.

Detailed Description Paragraph Right (21):
In the alternative embodiments of the supply assemblies shown in FIG. 1 and FIG. 4, the switch stages 20 and 20' can be formed by other suitable switch elements, for example IGBTs (insulated gate bipolar transistors). Separate unbiased diodes, which are already inherently present in MOS field effect transistors, may possibly then be connected with opposite polarity for the feedback. Further, more than three voltage sources can be provided or the voltage sources can exhibit different voltages. Switching to produce combinations of series and parallel circuitry, rather than only series or only parallel, are also possible.

CLAIMS:

1. A power amplifier comprising:

a supply assembly which produces an intermediate circuit voltage at a supply assembly output;

an output stage, comprising a plurality of driveable switch elements, connected to said supply assembly output for generating an output voltage at an output stage output from said intermediate circuit voltage;

said supply assembly comprising at least two voltage sources and at least one switch stage, and means for optionally connecting said at least two voltage sources in parallel or in series via said at least one switched stage; and

control means for driving said switch elements of said output stage and for operating said at least one switch stage for connecting said at least two voltage sources in series when a desired output voltage exceeds a predetermined threshold.

2. A power amplifier as claimed in claim 1 wherein said supply assembly comprises a plurality of branches connected in parallel, each of said branches containing one of said voltage sources and at least one diode connected in series with the voltage source in the branch.

3. A power amplifier as claimed in claim 1 wherein each of said two voltage sources has two poles of opposite polarity, and wherein said switch stage is connected between said at least two voltage sources to respective poles of the voltage sources of opposite polarity.

4. A power amplifier as claimed in claim 1 wherein said at least one switch stage comprises at least one diode for switching said at least two voltage sources in series in a feedback mode.

6. A power amplifier as claimed in claim 1 wherein said output stage contains a switch bridge, and wherein said output stage comprises means for generating said output voltage from said intermediate circuit voltage using said switch bridge by pulse-width modulation.

L10: Entry 3 of 5 File: USPT Feb 22, 2000

DOCUMENT-IDENTIFIER: US 6028476 A
TITLE: Power switched amplifer

Abstract Paragraph Left (1):
A power switched amplifier has a switched output stage which generates an output stage voltage and a filter stage coupled to the switched output stage for smoothing the output stage voltage. The smoothing effect of the filter stage is made to be variable with a control signal. Given little outlay, such an amplifier is capable of generating a well-smoothed output voltage with a high voltage change rate.

Brief Summary Paragraph Right (2):
The present invention is directed to a power switched amplifier of a type having a switched output stage which generates an output voltage, and a filter stage connected to the switched output stage for smoothing the output voltage. The present invention is further directed to a power switched amplifier of a type suitable for use as a gradient amplifier in a magnetic resonance tomography apparatus.

Brief Summary Paragraph Right (4):
An amplifier which delivers steep output voltage edges and generally exhibits a low residual ripple, for example, for use as a gradient amplifier of a nuclear magnetic resonance tomography apparatus.

Brief Summary Paragraph Right (5):
Generally, a nuclear magnetic resonance tomography apparatus has three gradient coils in which exactly regulated periodic currents respectively flow. For example, the current through each gradient coil in a cyclical current curve can reach values up to 300 A that must be adhered to with a precision in the mA range. The current curve can, for example, exhibit a cycle duration of 20 ms, whereby a current rise from0 to 300 A within 1 ms can be required. In order to enable these rapid changes in current, a voltage up to, for example, .+-.300 V having as vertical an edge steepness as possible must be applied to the gradient coil.

Brief Summary Paragraph Right (6):
Switched gradient amplifiers that, for example, work with a switching clock of 50 kHz are utilized in order to meet these demands, however, an undesired residual ripple (switching ripple) is produced in the output voltage by the switching. The residual ripple may cause resonance in sub-regions of the gradient coil, which is a complex structure with a plurality of local capacitances and inductivities. The high voltages thereby arising can produce local discharges that upset the patient and lead to image disturbances.

Brief Summary Paragraph Right (7):
German OS 40 07 566 discloses a switched power amplifier of the type initially described. This amplifier has a filter arrangement that contains four assemblies, each with a series inductance and a smoothing capacitor.

Brief Summary Paragraph Right (9):
The smoothing effect is also dependent on the switching clock frequency of the amplifier. A fast switching clock that exhibits a greater frequency separation from the useful signal is suppressed better by a low-pass filter. Given the high powers to be switched in the circumstances described above, however, an increase in the switching clock is only possible within certain limits and is also very complicated within these limits. A high switching clock causes high losses (that must be eliminated by cooling) and requires the use of more expensive components.

Brief Summary Paragraph Right (10):
An object of the present invention is to provide a power switched amplifier that, given little outlay, is capable of generating a well-smoothed output voltage with a high rate of voltage change.

Brief Summary Paragraph Right (12):
Due to this possibility of controlling the smoothing effect, the inventive amplifier need be designed for only a relatively low switching frequency without having to forego a strong filter effect. The amplifier is therefore economic in terms of manufacture and nonetheless supplies a high image quality given employment in a tomography apparatus.

Brief Summary Paragraph Right (14):
In one embodiment, the control unit obtains the information required for generating the control signal by measuring the output stage voltage of the amplifier. An input signal (reference value) of the amplifier, however, preferably is supplied to the control unit. In this case, the control unit can generate other control signals of the amplifier, for example pulse width modulated switching signals for switched components of the output stage.

Brief Summary Paragraph Right (20):
Depending on how many signal states the control signal can assume, the control element preferably acts as switch of a controllable resistor. The control element is preferably fashioned as MOSFET (MOS field effect transistor) or as bipolar transistor, particularly as an IGBT (insulated gate bipolar transistor).

Detailed Description Paragraph Right (1):
Each amplifier embodiment in FIG. 1 and FIG. 2 has a power pack 10, a switched output stage 12, a filter stage 14 and a control unit 16 as the main assemblies of a gradient amplifier. From an input voltage u.sub.1, the power pack 10 generates a stabilized intermediate circuit voltage u.sub.2 across inputs of the switched output stage 12. In a known way, the switched output stage 12 is formed by a bridge circuit composed of four switched components 18 operated by a control unit 16. The switched components 18 are fashioned as power MOSFETs, each an unbiased diode. Two of the switched components 18 are switched as a pair in series and each pair is connected to the intermediate circuit voltage u.sub.2. A pulse width-modulated output stage voltage u.sub.3 that serves as the input voltage for the filter stage 14 is taken at the transverse bridge arm, i.e. at the respective junctions between each pair of switched components 18.

Detailed Description Paragraph Right (2):
The filter stage 14 includes a capacitor assembly formed of two capacitors 20, 22 and a control element 24 and also has a series inductance 26 fashioned as a coil with an inductance of 50 .mu.H. These components form a low-pass filter for smoothing the output stage voltage u.sub.4. The smoothed voltage is supplied across inputs to a gradient coil (not shown) as the output voltage u.sub.4 of the gradient amplifier.

Detailed Description Paragraph Right (3):
The control unit 16 is connected to the control element 24 via a control line 28 and is connected via four switch lines 30 to the switched components 18, respectively. The control unit 16 has an input line 32 for a reference value signal.

Detailed Description Paragraph Right (4):
In the circuit according to FIG. 1, the two capacitors 20, 22 of the capacitor assembly are connected in series. The first capacitor 20 has a capacitance of 10 .mu.F, and the second capacitor 22 has a capacitance of 300 nF. The control element 24, whose structure is yet to be described, is connected in parallel with the second capacitor 22, i.e. in the current path of the first capacitor 20. When the control element 24 is transmissive, and thus bridges the second capacitor 22, the first capacitor 20 is effective for voltage smoothing with its full capacitance of 10 .mu.F, causing a high filter effect to be achieved. When, by contrast, the control element 24 inhibits, then the filter effect is slight because the output voltage u.sub.4 is across a capacitance of only approximately 290 nF. In intermediate stages of the conductivity of the control element 24, capacitances that lie between the aforementioned values and that are partially overlaid by the impedance of the control element 24 are effective for voltage smoothing.

Detailed Description Paragraph Right (5):

In the alternative embodiment shown in FIG. 2, the first capacitor with 10 .mu.F capacitance is connected in series with the control element 24. The second capacitor 22 with 300 nF capacitance is connected in parallel with the branch formed in this way. Depending on the level of conduction of the control element 24, the output voltage u.sub.4 is across a capacitance between 300 nF and somewhat over 10 .mu.F.

Detailed Description Paragraph Right (6):
FIG. 2 shows an embodiment of the control element 24 formed by of an IGBT 34 that is connected into the shunt arm of a rectifier bridge formed of four diodes 36. The gate of the IGBT 34 is connected to the control line 28. The rectifier bridge assures that the IGBT 34 only has to switch a current flow in one direction.

Detailed Description Paragraph Right (7):
Two IGBTs 34 arranged with opposite polarity and each having a preceding diode are provided in the alternative embodiment according to FIG. 4. The IGBTs 34 are driven in common. i.e. the IGBTs 34 either both transmit or both inhibit depending on the control signal c on the control line 28. To that end, different drive signals must be applied to the gates of the IGBTs 34, since their emitters lie at different potentials. These drive signals are generated from the control signal c by a suitable circuit. In a further alternative embodiment based on the circuit of FIG. 4, drive the two IGBTs 34 are separately driven in order to be able to define the smoothing properties of the amplifier dependent on the direction of the current.

Detailed Description Paragraph Right (8):
During operation of the exemplary embodiments of the gradient amplifier described herein, the control unit 16 generates four pulse width-modulated switching signals from the reference value signal (input signal) on the input line 32, these four pulse width-modulated switching signals being supplied respectively to the switched components 18 via the switch lines 30. Further, the control unit 16 generates a control signal c on the control line 28. The control signal c is a binary signal in order to place the control element 24 in either a transmissive condition or in an inhibited condition.

Detailed Description Paragraph Right (9):
If the output voltage u.sub.4 must rise or drop rapidly, for example given full modulation of the gradient amplifier, then a low capacitance of the capacitor assembly is set by switching the control element 24 (in the circuit according to FIG. 1 as well as in that according to FIG. 2) to a high-impedance condition. When the desired output voltage u.sub.4 is reached, the control element 24 is through-connected, so that the larger capacitor 20 becomes effective for voltage smoothing. Overall, thus, the time constant of the low-pass formed by the series inductance 26 and the capacitor assembly is suitably varied.

Detailed Description Paragraph Right (11):
The inventors currently view the gradient amplifier according to FIG. 1 with a control element according to FIG. 3 and a binary control signal c to be the best way of implementing the invention.

CLAIMS:

1. A power switched amplifier comprising:

a switched output stage which generates an output stage voltage at an output of said output stage;

filter means connected to said output of said output stage for smoothing said output stage voltage, said filter means having a variable filter effect which acts on said output stage voltage to produce an amplifier output voltage; and

control means for generating a control signal supplied to said filter means for varying said filter effect dependent on a rate of change to be achieved for said amplifier output voltage.

2. A power switched amplifier as claimed in claim 1 further comprising means for identifying when said rate of change of said amplifier output voltage exceeds a threshold, and wherein said control means comprises means for setting said control signal at a first control signal level when said rate of change of said amplifier output voltage exceeds said threshold, and otherwise setting said control signal to a second control signal level.

3. A power switched amplifier comprising:

a switched output stage which generates an output stage voltage at an output of said output stage;

filter means connected to said output of said output stage for smoothing said output stage voltage, said filter means having a variable filter effect which acts on said output stage voltage; and

means for generating a control signal supplied to said filter means for varying said filter effect, said filter means comprising: a capacitance having a current path connected across said output voltage, and a control element in said current paths supplied and driven by said control signal.

4. A power switched amplifier as claimed in claim 3 wherein said control element comprises an element functioning as a switch actuatable by said control signal.

5. A power switched amplifier as claimed in claim 3 wherein said control element comprises an element functioning as a resistor having a resistance controllable by said control signal.

6. A power switched amplifier as claimed in claim 3 wherein said control element comprises a rectifier bridge formed by four diodes, and having a rectifier bridge shunt arm, and wherein said control element comprises an IGBT connected in said rectifier bridge shunt arm.

7. A power switched amplifier as claimed in claim 3 wherein said capacitance comprises a capacitance which is variable by said control signal by a factor of at least 10.

8. A power switched amplifier as claimed in claim 7 wherein said capacitance comprises a capacitor which is variable by said control signal by a factor of at least 30.

9. A power switched amplifier as claimed in claim 3 wherein said capacitance comprises two capacitors connected in series across said output stage voltage, and wherein said control element is connected in parallel with one of said two capacitors.

10. A power switched amplifier as claimed in claim 3 wherein said capacitance comprises two capacitors connected in parallel across said output stage voltage, and wherein one of said two capacitors is connectable and disconnectable across said output stage voltage by said control element.

11. A power switched amplifier as claimed in claim 3 wherein said filter means further comprises an inductance connected in series with said capacitance.

Search Results - Record(s) 1 through 1 of 1 returned.

1. Document ID: US 4820986 A

L18: Entry 1 of 1 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

INVENTOR-INFORMATION:

NAME	CITY	STATE	ZIP CODE	COUNTRY
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Coxon; Ronald J.	Wollaton			GBX

US-CL-CURRENT: 324/322; 363/98

Image

Term	Documents
(8 AND 17).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	1
(L17 AND L8).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	1

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1. Document ID: US 6034565 A

L13: Entry 1 of 3 File: USPT Mar 7, 2000

US-PAT-NO: 6034565
DOCUMENT-IDENTIFIER: US 6034565 A

TITLE: Power amplifier for use in an NMR tomography apparatus

DATE-ISSUED: March 7, 2000

INVENTOR-INFORMATION:

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US-CL-CURRENT: 330/10; 330/251

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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2. Document ID: US 5270657 A

L13: Entry 2 of 3 File: USPT Dec 14, 1993

US-PAT-NO: 5270657
DOCUMENT-IDENTIFIER: US 5270657 A

TITLE: Split gradient amplifier for an MRI system

DATE-ISSUED: December 14, 1993

INVENTOR-INFORMATION:

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US-CL-CURRENT: 324/322; 324/318

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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☐ 3. Document ID: US 4820986 A

L13: Entry 3 of 3 File: USPT Apr 11, 1989

US-PAT-NO: 4820986
DOCUMENT-IDENTIFIER: US 4820986 A

TITLE: Inductive circuit arrangements

DATE-ISSUED: April 11, 1989

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US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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Term	Documents
PARALLEL.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	2032529
PARALLELS.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	9093
SERIES.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	1272550
SERY.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	178
SERYS.DWPI,TDBD,EPAB,JPAB,USPT,PGPB.	47
(12 AND (SERIES OR PARALLEL)).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	3
(L12 AND (PARALLEL OR SERIES)).USPT,PGPB,JPAB,EPAB,DWPI,TDBD.	3

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Previous Page Next Page

L13: Entry 1 of 3 File: USPT Mar 7, 2000

DOCUMENT-IDENTIFIER: US 6034565 A
TITLE: Power amplifier for use in an NMR tomography apparatus

Abstract Paragraph Left (1):
A power amplifier has an amplifier assembly and a resonant assembly with a resonant capacitor and a control element. A parallel resonant circuit can be formed by the resonant capacitor and a load that can be connected to the amplifier. An output voltage or an intermediate circuit voltage of the amplifier can be applied at the resonance capacitor via the control element. An NMR tomography apparatus has at least one such power amplifier. The power amplifier can be universally used with low components outlay and is able to generate a number of signal forms.

Brief Summary Paragraph Right (2):
The present invention is directed to a power amplifier of the type suitable for use in an NMR tomography apparatus, the power amplifier being of the type having a voltage source and a resonant assembly connected in parallel with the voltage source, the resonant assembly including a resonant capacitor connected in series with a control element.

Brief Summary Paragraph Right (4):
An NMR tomography apparatus usually has three gradient coils in which precisely controlled periodic currents flow. The current behavior curve is dependent on the imaging method used. In a high-speed method, for example, as the EPI (echoplanar) method, it is particularly necessary to generate very steep and rapid consecutive leading and trailing edges of current. It thus can be necessary to build up and dismantle a current flow of 200 A in a gradient coil (with an inductivity of 1 mH, e.g.) within time intervals of 0.5 ms. The EPI method is described in detail in European Application 0 076 0054.

Brief Summary Paragraph Right (5):
To satisfy these high demands, it is known to use a resonant circuit formed of the gradient coil and a capacitor. The gradient currents are sinusoidal at least in sections thereof.

Brief Summary Paragraph Right (6):
European Application 0 227 411 discloses a gradient amplifier of the general type initially described. A gradient coil is arranged in a shunt arm of a circuit bridge. A resonant capacitor is connected in parallel with the circuit bridge via a switch element. A constant voltage is applied at the circuit bridge via a diode.

Brief Summary Paragraph Right (7):
U.S. Pat. No. 4,628,264 discloses a gradient amplifier wherein a resonant capacitor and a gradient coil form a parallel resonant circuit. A switch element or a switch bridge is arranged in the resonant circuit in order to separate or change the polarity of the connection between the resonant capacitor and the gradient coil. Amplifiers which are permanently connected with the resonant capacitor are provided for compensating losses during the resonant oscillations.

Brief Summary Paragraph Right (8):
German OS 41 27 529 discloses a gradient amplifier wherein a resonant capacitor is arranged in a shunt arm of a switch bridge. The switch bridge, a gradient coil and an amplifier assembly together form a serial resonant circuit. In the operation of the gradient amplifier, the amplifier assembly serves to generate individual sections of each gradient pulse in a non-resonant fashion.

Brief Summary Paragraph Right (9):
The circuits according to European Application 0 227 411 and the U.S. Pat. No. 4,628,264 are able to generate only a limited number of different current profiles. Thus these circuits are not universally usable. Moreover, the embodiments with switch bridges result in a high component outlay. The circuit proposed in German OS 41 27 529 is likewise very expensive, because another switch bridge is required in addition to a complete amplifier assembly, typically constructed as a switched amplifier.

Brief Summary Paragraph Right (10):
It is an object of the present invention to provide a power amplifier suitable for use in an NMR tomography apparatus which avoids the aforementioned problems associated with the prior art and which can by universally with a low outlay for components and which is able to generate a number of signal forms.

Brief Summary Paragraph Right (11):
The above object is achieved in accordance with the principles of the present invention in a power amplifier, particularly a gradient amplifier for an NMR tomography apparatus, having an amplifier assembly forming a voltage source, a resonant assembly connected in parallel with the amplifier assembly forming the voltage source and including a resonant capacitor connected in series with a control element, wherein the amplifier assembly and the resonant assembly operate in combination to generate an output voltage of the power amplifier.

Brief Summary Paragraph Right (12):
The above object is also achieved in a power amplifier constructed in accordance with the invention, particularly a gradient amplifier for an NMR tomography apparatus, having an intermediate circuit assembly which generates an intermediate circuit voltage, a resonant assembly including a resonant capacitor and a control element operable to connect and disconnect the resonant capacitor across the intermediate circuit voltage, and a switched output stage connected across the resonant capacitor, the switched output stage being configured to provide a switched output stage voltage by means of pulse-width modulation in a first mode of the power amplifier, this switched output stage voltage being employed in the generation of the output voltage. The switched output stage is also operable in a second mode of operation of the power amplifier to form a parallel resonant circuit between the resonant capacitor and a load which can be connected to the power amplifier.

Brief Summary Paragraph Right (13):
A power amplifier is inventively created which is able to generate a number of different current forms and is particularly capable for EPI. Components are saved, inasmuch as the invention uses a parallel resonant circuit at which either an output current or an intermediate circuit current of the amplifier assembly can be applied. The inventive amplifier thus can be produced particularly cost-effectively. The invention can be used in all types of power amplifiers. Besides gradient amplifiers, these are power amplifiers used in devices for inductive heating, in particular.

Brief Summary Paragraph Right (14):
As used herein the term "output voltage of the power amplifier," means a voltage which can be attached to a load without intermediate circuit of other switch components of the power amplifier. This does not mean, however, that the output voltage of the amplifier would have to be directly across the load. For example, a number of amplifiers can be coupled and connected together to the load, or a filtering circuit can be provided within the amplifier or between the amplifier and the load.

Brief Summary Paragraph Right (15):
The amplifier assembly is preferably constructed as high-value power amplifier which is able to supply the load with a desired current in a first, non-resonant mode. Such an amplifier assembly generates the output current preferably by pulse-width modulation by means of a switched output stage. A second, resonant mode is preferably further provided in which a resonant oscillation and/or a temporary over-voltage occurs through resonance.

Brief Summary Paragraph Right (17):
In the second, resonant mode, a parallel resonant circuit is formed between the load and the resonance capacitor by the insertion of a control element and/or by the insertion of the switch output stage. In these embodiments, in the second mode only the control element or only the switched output stage or both have the resonant

current flowing therein.

Brief Summary Paragraph Right (19):
The control element is preferably constructed as an electronic switch which can be dependent or independent of the current direction. In alternative embodiments, the control element can act as an electronically controllable resistor. The control element preferably includes one or more MOSFETs (MOS-Field Effect Transistors) or IGBTs (insulated gate bipolar transistors) and possibly one or more diodes.

Brief Summary Paragraph Right (20):
In a preferred embodiment, a filtering circuit is provided to filter the output voltage of the power amplifier. This is particularly the case if a pulse-width-modulated signal serves to generate the output voltage in the non-resonant mode. The filtering circuit preferably has a filtering frequency (cut-off frequency) which is lower than the switch frequency of the switch output stage by a factor of 0.5 to 0.8. For example, the filter frequency can equal 30 kHz given a switch frequency of 50 kHz.

Brief Summary Paragraph Right (21):
In an NMR tomography apparatus, the inventive power amplifier preferably serves as the power supply of a gradient coil. In preferred embodiments, in order to achieve particularly strong voltages or currents, amplifier arrangements are provided which are connected in series or in parallel at the output side and which include an inventive power amplifier. Such an amplifier arrangement preferably further contains at least one amplifier means which does not have its own resonant assembly (base amplifier) and/or at least one optionally connectable constant-voltage source.

Detailed Description Paragraph Right (1):
In the power amplifier depicted in FIG. 1 which is configured as gradient amplifier of an NMR tomography apparatus, an amplifier assembly 10 serving as a voltage source and a resonant assembly 12 are connected in sequence and are connected to a gradient coil which forms a predominantly inductive load 14. A control unit 16 is further provided for controlling all the components of the power amplifier.

Detailed Description Paragraph Right (3):
A switched output stage 26 of the amplifier assembly 10 has four switch components 28 in a bridge arrangement. The switch components 28 are constructed as power MOSFETS, each having a recovery diode. The switch components 28 are arranged in two series-connected pairs, each having the intermediate circuit u.sub.Z thereacross. At the shunt arm of the bridge--i.e. at the respective junctions of the two switch components 28 in the pairs--an output u.sub.S is tapped, which serves as an input voltage for a filtering stage 30 of the amplifier assembly.

Detailed Description Paragraph Right (5):
The resonant assembly 12 is connected in parallel with the filtering capacitor 34 and the load 14, so that the output voltage u.sub.A is likewise across at the resonant assembly 12, or is generated in a resonant mode by the resonant assembly 12 in cooperation with the load 14. The resonant assembly 12 contains a resonant capacitor 38 with a capacitance of approximately 10 .mu.F which is connected in series with a control element 40. The resonant capacitor 38 can be applied at the load 14 and separated therefrom by means of the control element 40, whose construction will be described.

Detailed Description Paragraph Right (6):
The control unit 16 is connected with the four switch components 28 via four respective lines 42 is connected to the control element 40 via a control line 44. The power amplifier according to FIG. 1 can function in many different modes as well as in one of several stages.

Detailed Description Paragraph Right (7):
In a first, non-resonant mode the control element 40 is highly resistive, so that the resonant capacitor 38 is decoupled and does not exert any influence. The output voltage u.sub.A is generated in known fashion in that the switch output stage 26 generates a precisely controlled output stage voltage u.sub.S from the intermediate circuit voltage uZ by pulse-width modulation. A residual ripple is filtered out by the filtering stage 30, and the filtered voltage u.sub.F is across the load 14 as an output voltage u.sub.A.

Detailed Description Paragraph Right (8):

In a second, resonant mode the control element 40 conducts, so that the parallel resonant circuit formed by the resonant capacitor 38 and the load 14 is closed, and a sinusoidal, resonant oscillation arises. The switch components 28 of the switched output stage 26 are discharged, because the actual oscillating current flows outside the switched output stage 26. The switched output stage 26 can assume a highly resistive state if, for example, all switch components 28 are in a blocking state. In this case, the resonant oscillation is relatively free, and the output stage voltage u.sub.S is generated by the resonant circuit and not by the switched output stage 26. Alternatively, the two series inductances 32 can be connected to each other with low resistivity via the switched output stage 26, so that the resonant oscillation is influenced by the filtering stage 30, but not by the output voltage u.sub.S generated by the switched output stage 26.

Detailed Description Paragraph Right (9):
Instead of a pure resonant operation, the control unit 16 can further assume a mode in which the resonant capacitor 38 is connected, and a mode wherein the output stage voltage u.sub.S generated by the switched output stage 26 influences the resonant oscillation. The effect of the switched output stage 26 can be variably strong. Thus the switched output stage 26 can be used to modify the sinusoidal current profile of the resonant oscillation or to compensate an attenuation of the resonant oscillation through losses (for example, at the ohmic resistance of the load 14 or at the control element 40).

Detailed Description Paragraph Right (10):
Finally, modes are also possible in which the current flow through the load 14 is generated predominantly by the switched output stage 26, and the control element 40 forms a larger or smaller resistance. The resonant capacitor 38 can thus be pre-charged to a desired voltage which cannot however exceed the output voltage u.sub.A. In an alternative embodiment of the circuit of FIG. 1, a divided pre-charging circuit can be provided for the resonant capacitor 38, with which circuit higher pre-charging voltages can also be generated.

Detailed Description Paragraph Right (12):
The power amplifier depicted in FIG. 2 is constructed similarly to the amplifier according to FIG. 1, as described above. The amplifier according to FIG. 2 differs itself from the amplifier according to FIG. 1 in that the resonant assembly 12 is connected in the intermediate circuit of the amplifier assembly 10. More specifically, the control element 40 of the resonant assembly 12 is connected in the current path running from the intermediate circuit assembly 20 to the switched output stage 26, and the resonant capacitor 38 is connected in parallel with the switched output stage 26 at the input side. Thus a resonant circuit voltage u.sub.R, rather than the intermediate circuit voltage u.sub.Z, is directly across the switched output stage u.sub.R. In the circuit according to FIG. 2, the load 14 is connected directly to the filtering stage 30 at the output side without resonant components being connected in parallel.

Detailed Description Paragraph Right (13):
In the operation according to FIG. 2, the control element 40 conducts in the first non-resonant mode. The resonant capacitor 38 is thus connected in parallel with the buffer capacitor 24--which is much larger (e.g. by a factor of 100)--so that the resonance frequency shifts into a region which can be compensated by a current regulator of the control assembly 16. The power amplifier then functions in the manner described above, whereby the oscillating current voltage uR is therein essentially the same as the intermediate circuit voltage uZ.

Detailed Description Paragraph Right (14):
In the second, resonant mode, the control element 40 is highly resistive. The parallel resonant circuit formed between the resonant capacitor 38 and the load 14 is disposed between the switched output stage 26 and the filtering stage 30, which is continuously active.

Detailed Description Paragraph Right (15):
In the resonant mode the switch components 28 can be controlled by the control unit 16 such that a connection is produced between a one terminal of the resonance capacitor 38 and a one output terminal 36, this connection remaining the same during this mode. In this case a free sinusoidal oscillation arises. It is also possible, however, to influence the form of oscillation by a suitable control of the switch components 28. The resonant circuit can be interrupted, for example, if the resonant capacitor 38 has reached its maximal charge and the current flow in the resonant

circuit is exactly zero. A current flow can likewise be maintained in the load 14, by connecting the output terminals 36 with low resistivity via the filtering stage 30 and the switched output stage 26.

Detailed Description Paragraph Right (17):
In the amplifier according to FIG. 2, the resonant capacitor 38 can be pre-charged to the intermediate circuit voltage uZ in order to enable a rapid and immediate commencement of oscillation. In such a third mode, the control element 40 is through-connected and the connection between the resonant capacitor 38 and the load 14 is interrupted by the opened switch components 28 in the switched output stage 26. In the circuit depicted in FIG. 2, the intermediate circuit voltage can be set in a graduated or a continuous fashion in order to make available various pre-charging voltages, particularly those which differ from the intermediate circuit voltages uZ arising in the first mode of the power amplifier.

Detailed Description Paragraph Right (19):
FIG. 3 depicts shows an embodiment of the control element 40. An IGBT is arranged in the shunt arm of a rectifier bridge formed from four diodes 48. The gate of the IGBT 46 is connected to a control terminal 50 which is connected to the control line 44 shown in FIGS. 1 and 2. The rectifier bridge has two switch terminals 52 with which the control element 40 is connected into the circuit to be switched. Due to the rectifier bridge, it is insured that the IGBT 46 need only switch one current flow in one direction.

Detailed Description Paragraph Right (20):
In the alternative embodiment of the control element according to FIG. 4, two IGBTs 46 connected with opposite polarities are provided with respective pre-charged diodes 48 and respective control terminals 50. In this embodiment, the IGBTs 46 are jointly controlled. This means that, depending on a control signal on the control line 44, the IGBTs 46 always either both conduct or both block, or both have approximately the same resistance. To this end, different drive signals must be applied at the control terminals 50, since the emitters of the IGBTs 46 are at different potentials. These drive signals are generated by a suitable circuit from the control signal on the control line 44.

Detailed Description Paragraph Right (21):
In another alternative embodiment based on the circuit in FIG. 4, the two IGBTs 46 are driven separately in order to be able to define the conductive properties of the control element 40 dependent on the current direction. A power amplifier with such a control element 40 is able to generate an even larger bandwidth of various current profiles.

Detailed Description Paragraph Right (22):
In the use of the control element 40 in the circuit according to FIG. 1, its components are dimensioned such that their voltage stability suffices to block the full output voltage u.sub.A in the non-resonant mode of the power amplifier, and its current loading capacity suffices to conduct the full resonant current in the resonant mode. This applies given the use of the control element 40 in the circuit according to FIG. 2, accordingly.

Detailed Description Paragraph Right (23):
The power amplifier according to FIG. 2 with a control element according to FIG. 3 is presently considered by the inventor as the best mode of the inventive power amplifier. Furthermore, the inventor presently considers an NMR tomography apparatus in which an inventive power amplifier and a base amplifier are connected in series and connected to the load 14 as the best mode of the inventive NMR tomography apparatus.

CLAIMS:

1. A power amplifier comprising:

an amplifier assembly forming a voltage source;

a resonant assembly connected in parallel across said amplifier assembly, said resonant assembly comprising a resonant capacitor and a control element connected in series; and

said amplifier assembly being operable for generating an output voltage of said

power amplifier in a non-resonant mode of said power amplifier, and said resonant assembly being operable for generating said output voltage of said power amplifier in a resonant mode of said power amplifier.

2. A power amplifier as claimed in claim 1 wherein said amplifier assembly comprises a switched output stage comprising means for producing a switched output stage voltage by pulse-width modulation in said non-resonant mode.

3. A power amplifier as claimed in claim 2 comprising filtering means for filtering said switched output stage voltage, said filtering means being active only in said non-resonant mode.

4. A power amplifier as claimed in claim 2 comprising filtering means for filtering said switched output stage voltage, said filtering means being active only in said resonant mode.

5. A power amplifier as claimed in claim 2 comprising filtering means for filtering said switched output stage voltage, said filtering means being active both in said non-resonant and resonant modes.

7. A power amplifier as claimed in claim 2 further comprising control means for driving said control element and for driving said switched output stage.

8. A power amplifier comprising:

an intermediate circuit assembly which generates an intermediate circuit voltage;

a resonant assembly comprising a resonant capacitor and a control element connected across said intermediate circuit voltage, said control element being operable to connect and disconnect said resonant capacitor across said intermediate circuit voltage; and

a switched output stage connected across said resonant capacitor, said switched output stage comprising means, in a first mode, for producing a switched output stage voltage by pulse-width modulation of said intermediate circuit voltage, said switched output stage voltage being employed for generating an output voltage, and, in a second mode, for forming a parallel resonant circuit between said resonant capacitor and a load.

10. A power amplifier as claimed in claim 8 wherein said switched output stage comprises means for conducting a resonant current in said second mode.

13. A power amplifier as claimed in claim 8 wherein said control element comprises an IGBT connected in a shunt arm of a diode bridge.

14. A power amplifier as claimed in claim 8 wherein said control element comprises two IGBTs connected in parallel with opposite polarity.

15. A power amplifier as claimed in claim 8 comprising filtering means for filtering said switched output stage voltage, said filtering means being active only in said first mode.

16. A power amplifier as claimed in claim 8 comprising filtering means for filtering said switched output stage voltage, said filtering means being active only in said second mode.

17. A power amplifier as claimed in claim 8 comprising filtering means for filtering said switched output stage voltage, said filtering means being active both in said first and second modes.

18. A power amplifier as claimed in claim 8 further comprising control means for driving said control element and for driving said switched output stage.

19. A power amplifier comprising:

an amplifier assembly forming a voltage source;

a resonant assembly connected in parallel across said amplifier assembly forming a voltage source, said resonant assembly comprising a resonant capacitor and a control

element connected in series;

said amplifier assembly and said resonant assembly, in combination, comprising means for generating an output voltage; and

said control element being a control element selected from the group consisting of an IGBT connected in a shunt arm of a diode bridge, and two IGBTs connected in parallel with opposite polarity.

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☐ 1. Document ID: US 5270657 A

L17: Entry 1 of 2   File: USPT   Dec 14, 1993

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DOCUMENT-IDENTIFIER: US 5270657 A

TITLE: Split gradient amplifier for an MRI system

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INVENTOR-INFORMATION:

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TITLE: Inductive circuit arrangements

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US-CL-CURRENT: 324/322; 363/98

Full | Title | Citation | Front | Review | Classification | Date | Reference | Sequences | Attachments | KWIC
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DOCUMENT-IDENTIFIER: US 5270657 A
TITLE: Split gradient amplifier for an MRI system

Abstract Paragraph Left (1):
A gradient amplifier for use in magnetic resonance imaging equipment employs a low voltage DC power supply connected in series between a pair of higher voltage DC power supplies, the latter supplies serving to provide increased power for rapid gradient switching and the former supply providing correction current to produce the desired voltage output. The high voltage DC power supplies preferably comprise multiple DC units which can be combined to provide finer steps of control prior to correction by the lower voltage supply. The low voltage DC power supply preferably comprise one or more linear amplifiers connected in series, or one or more switchmode amplifiers connected in series. The DC power supplies are controlled in an open loop manner from a gradient signal that designates the desired current for the gradient coil and the amplifiers are operated in a closed loop responding to to a feedback signal from the gradient coil.

Brief Summary Paragraph Right (1):
This invention relates to magnetic resonance imaging apparatus and more specifically to high current, gradient power supplies for use in such apparatus.

Brief Summary Paragraph Right (2):
Magnetic resonance imaging ("MRI") has developed as an important tool in diagnostic medicine. In MRI, as is understood by those skilled in the art, a body being imaged is held within a uniform magnetic field oriented along a Z-axis of a Cartesian coordinate system.

Brief Summary Paragraph Right (3):
The spins of the nuclei of the body are excited into precession about the z-axis by means of a radio frequency (RF) pulse. The decaying precession of these excited spins produces a nuclear magnetic resonance (NMR) signal whose amplitude is dependant, among other factors, on the number of precessing nuclei per volume within the imaged body. This number of spins is termed the "spin density".

Brief Summary Paragraph Right (4):
An image of the spin density, or other characteristics revealed by the NMR signal, may be produced by impressing precisely controlled magnetic gradient fields G.sub.x, G.sub.y, and G.sub.z along the X, Y and Z axes. These gradient fields, created by gradient coils driven by a gradient amplifier system, encode position information into the NMR signals through phase and frequency shifting of the NMR signal for spins in different locations.

Brief Summary Paragraph Right (5):
Referring to FIG. 1, a typical "spin echo" pulse sequence for acquiring data under the spin warp MRI technique includes: 1) a Z-axis gradient G.sub.z activated during a first 90.degree. RF pulse to select the image slice in the Z-axis, 2) a Y-axis gradient field G.sub.y to phase encode the precessing nuclear spins in the y direction, and 3) an X-axis gradient G.sub.x activated during the acquisition of the NMR signal to frequency encode the precessing nuclear spins in the x direction. Two such NMR acquisitions, S.sub.1 and S.sub.1 ', the latter inverted and summed with the first, comprise the NMR signal of a single view "A" under this sequence. Note that the y gradient field G.sub.y changes between view "A" and subsequent view "B". This pulse sequence is described in detail in U.S. Pat. No. 4,443,760, entitled: "Use of Phase Alternated RF Pulses to Eliminate Effects of Spurious Free Induction Decay Caused by Imperfect 180 Degree RF Pulses in NMR Imaging", and issued Apr.

17,1984, assigned to the same assignee as the present invention and incorporated by reference.

Brief Summary Paragraph Right (6):
A set of NMR signals comprised of many views may be "reconstructed" to produce an image of a single slice of an imaged object according to well understood techniques. Multiple slices are needed to generate information over three dimensions of the imaged object.

Brief Summary Paragraph Right (7):
The speed with which slice images may be obtained is limited, to a large extent, by the speed with which the gradient fields may be changed. The gradient coils are substantially inductive loads and hence obtaining higher speed switching of the gradient fields requires amplifiers capable of producing correspondingly higher voltages, often on the order of 2,000 volts. These higher voltages, together with the high currents required by the gradient coils (of 200 Amperes or more), demand amplifiers capable of extremely high power output.

Brief Summary Paragraph Right (8):
The gradient amplifiers must also be capable of accurate control of the gradient current delivered to the gradient coils and should allow the maximum possible flexibility in the generation of gradient waveforms of arbitrary shape for present and future imaging techniques. For this reason, high powered linear amplifiers are most commonly used.

Brief Summary Paragraph Right (9):
Previously, the power supply for a gradient coil utilized a single voltage inverter. Because of the relatively high voltages being switched, the single inverter had to use transistors capable of handling such voltages. It is desirable to be able to switch the high voltage with lower rated transistors.

Brief Summary Paragraph Right (10):
This invention relates to a gradient amplifier system in which DC power supplies are connected in tandem with conventional linear gradient amplifiers to boost the effective gradient power to the gradient coils.

Brief Summary Paragraph Right (11):
Specifically, a DC power supply receiving a gradient signal has an output connected to the gradient coil for generating a first voltage component, selectable from a discontinuous range of output voltages, and approximating a desired magnetic gradient field. A feedback sensor is connected to the gradient coil for producing a feedback signal which is used to control an amplifier. The amplifier has an output also connected to the gradient coil for generating in the gradient coil a second voltage component, but within another continuous range of output voltages. The feedback signal and the gradient signal are used by the amplifier to adjust the second voltage component so that the sum of the first and second voltage components provides the desired magnetic gradient field.

Brief Summary Paragraph Right (12):
It is thus one object of the invention to obtain the power efficiency and simplicity of using a DC source to drive a gradient coil, while still maintaining the ability to precisely generate arbitrary waveforms. DC power supplies may employ relatively simple construction or may operate with extremely low power dissipation. The amplifier serves to "fill in" the stepped output of the DC power supply to provide effective linear control. The correction provided by the amplifier permits the DC power supplies to have relatively little internal regulation. In fact, the DC power supplies may be no more than charged capacitors, provided the amplifier has the range to compensate for their varying output.

Brief Summary Paragraph Right (13):
It is another object of the invention to take advantage of the intermittent power demands of gradient coils. The DC power supplies provide power for peak demand and may accumulate energy in storage capacitors or the like, at other times to thus require lower powered components.

Brief Summary Paragraph Right (14):
In one embodiment, the DC power supply may be constructed of multiple DC sources, each source providing an incremental voltage to the gradient coils together to offer several output voltage levels. The values of the voltages from each DC source may

stand in binary relationship with the voltages of the other sources. The gradient current is, in either case, generated by switching the appropriate combination of DC sources together.

Brief Summary Paragraph Right (15):
It is thus another object of the invention to provide a plurality of DC sources that may, together, better approximate the voltage needed to generate the desired gradient current, thereby allowing the amplifier to be correspondingly reduced in power output.

Brief Summary Paragraph Right (16):
In one embodiment the DC power supplies may include large storage capacitors capable of receiving energy from the inductive gradient coils when the gradient field is reduced.

Brief Summary Paragraph Right (17):
It is another object of the invention, therefore, to take advantage of the inductive, energy storing nature of the gradient coils. The peak power demanded of the gradient amplifiers is during periods when the gradient strength must be changed. In these periods, energy is added to or subtracted from the energy stored in the gradient coils. The use of capacitors in the output of the DC power supplies allows this stored energy to be recaptured from the gradient coils during periods when the gradient coil strength is being reduced and added again during periods when the gradient signal is being increased.

Brief Summary Paragraph Right (18):
Not all energy may be successfully recaptured from the gradient coils by the storage capacitors. Therefore, they soon need supplemental recharging.

Brief Summary Paragraph Right (19):
In a further embodiment, the storage capacitors may be recharged by the amplifier during the changing of the gradient level. A capacitor reference voltage is used to indicate a desired peak capacitor voltage corresponding to a first gradient current flow. A sample of the peak voltage on the capacitor is used to produce a peak voltage signal which together with the reference voltage generates an error signal. The error signal produces a current to add to the first and second currents in the gradient coil, to move the peak capacitor voltage toward the value of the reference voltage.

Brief Summary Paragraph Right (21):
Other objects and advantages besides those discussed above shall be apparent to those experienced in the art from the description of a preferred embodiment of the invention which follows. In the description, reference is made to the accompanying drawings, which form a part hereof, and which illustrate one example of the invention. Such example, however, is not exhaustive of the various alternative forms of the invention, and therefore reference is made to the claims which follow the description for determining the scope of the invention.

Drawing Description Paragraph Right (1):
FIG. 1 is a graphical representation of an MRI pulse sequence showing gradient field waveforms G.sub.x, G.sub.y, and G.sub.z ;

Drawing Description Paragraph Right (2):
FIG. 2 is a block diagram of an MRI apparatus incorporating the amplifiers of the present invention;

Drawing Description Paragraph Right (3):
FIG. 3 lied block diagram of one of the gradient amplifiers of FIG. 2 showing the interconnections between amplifiers and DC power supplies;

Drawing Description Paragraph Right (4):
FIG. 4 is a schematic diagram of a first embodiment of the DC power supplies of FIG. 3, showing the positioning of an energy storage capacitor bank;

Drawing Description Paragraph Right (5):
FIG. 5 is a block diagram of a controller for switching the DC power supply of FIG. 4 in response to a gradient signal;

Drawing Description Paragraph Right (7):

FIG. 7(a) is a graph of a hypothetical gradient signal input to the gradient amplifier of FIG. 4;

Drawing Description Paragraph Right (8):
FIG. 7(b) is a graph of the derivative of the gradient signal of Figure 7(a) such as is used to control the DC power supply of FIG. 4;

Drawing Description Paragraph Right (9):
FIG. 7(c) is a graph of the voltage on the capacitor bank of the DC power supply of FIG. 4 for the gradient signal of FIG. 7(a);

Drawing Description Paragraph Right (10):
FIG. 7(d) is a graph of a current correction signal used to restore the charge of the capacitor bank of the DC power supply of FIG. 4 caused by resistive or other losses;

Drawing Description Paragraph Right (11):
FIG. 7(e) is a graph of the gradient coil current produced by the gradient signal of FIG. 7(a) and the correction current of FIG. 7(d);

Drawing Description Paragraph Right (12):
FIG. 8 is a schematic diagram of a second embodiment of the DC power supplies of FIG. 3, showing the use of multiple DC sources having binary weighted outputs;

Drawing Description Paragraph Right (13):
FIG. 9 is a block diagram of a controller for switching the DC power supply of FIG. 8 in response to a gradient signal;

Drawing Description Paragraph Right (14):
FIG. 10 is a simplified block diagram of another gradient amplifier according to the present invention;

Drawing Description Paragraph Right (15):
FIG. 11 is a simplified block diagram of a gradient amplifier which incorporates a pair of switchmode amplifiers as the low voltage supplies;

Drawing Description Paragraph Right (16):
FIG. 12 is a simplified block diagram of a gradient amplifier which has a single switchmode amplifier; and

Drawing Description Paragraph Right (17):
FIG. 13 is a block schematic diagram of a gradient amplifier which utilizes four high voltage power supplies.

Detailed Description Paragraph Right (1):
Referring to FIG. 2, the RF and gradient field signals used in MRI pulse sequences, such as that shown previously in FIG. 1 for spin warp imaging, are generated by a pulse control module 12 which synthesizes properly timed pulse sequences under the control of a computer 10.

Detailed Description Paragraph Right (2):
The pulse control module 12 communicates by means of a digital signal 20 to a gradient waveform preprocessor 14 which converts the digital signal into three analog gradient signals 16, one for each gradient axis. The analog gradient signals 16 are communicated to a set of three identical gradient amplifier systems 42 each connected to a gradient coil within assembly 23 to produce the gradient fields G.sub.x, G.sub.y, and G.sub.z as described above.

Detailed Description Paragraph Right (3):
Each gradient coil in assembly 23 consists of a number of turns of a copper conductor and is arranged in proximity to a patient 18 in the magnet assembly 40. The magnet assembly 40 also contains the superconducting magnet for producing the polarizing field B.sub.0 as is generally described in U.S. Pat. No. 4,737,716 entitled: "Self-Shielded Gradient Coils For Nuclear Magnetic Resonance Imaging" issued Aug. 12, 1988, assigned to the same assignee as the present invention and incorporated herein by reference.

Detailed Description Paragraph Right (4):
The pulse control module 12 also controls a radio frequency synthesizer 32, which is

part of an RF transceiver, portions of which are enclosed by block 31. The pulse control module 12 additionally controls an RF modulator 30 which modulates the output of the radio frequency synthesizer 32. The resultant RF signals, amplified by power amplifier 28 and applied to RF coil 24 through transmit/receive switch 26, are used to excite the nuclear spins of the imaged patient 18.

Detailed Description Paragraph Right (5):
The NMR signals from the excited nuclei are picked up by the RF coil 24 in the magnet assembly 40 and presented to preamplifier 38 through transmit/receive switch 26, to be amplified and then processed by a quadrature phase detector 36. The detected signals are digitized by a high speed A/D converter 34 and applied to computer 10 for processing to produce images of the patient 18.

Detailed Description Paragraph Right (6):
Referring now to FIGS. 2 and 3, each gradient amplifier 42, associated with a particular gradient coil 22 within assembly 23 for the three gradient axes Gx, Gy and Gz, includes a series connected chain of two linear amplifiers 44 and two DC power supplies 46. This series connected chain is, in turn, connected across a gradient coil 22 to provide power to that coil. Each linear amplifier 44 provides a voltage output that is a simple multiplicative scaling of an analog signal at its input 43. Further, the output of the linear-amplifier 44 is substantially continuous, that is, the output is not subject to movement in discrete steps but is controllable, by the signals at its input 43, to an arbitrary value within the output range of the linear amplifier. Each linear amplifier 44 is designed in bridge configuration to have a "floating output". That is, it produces an output voltage defined with respect to two terminals neither of which is referenced to a ground that is common with the other circuit elements of the gradient amplifier 42. The floating output allows the voltage output of the linear amplifier 44 to be added to other voltage sources simply by connecting it in series with such other sources. Linear amplifiers 42 are known in the art and are described in U.S. Pat. No. 3,808,545 entitled: "High Power Bridge Audio Amplifier" which description is incorporated herein by reference.

Detailed Description Paragraph Right (7):
The DC power supplies 46, as will be described in more detail below, provide only discrete steps of output voltage and thus may be contrasted to the linear amplifiers 44 by the fact that their outputs are not a continuous function of an input value. In a simplest embodiment, the DC power supplies 46 are capable of only three voltage outputs: zero volts and a predetermined voltage of either of two polarities.

Detailed Description Paragraph Right (8):
Like the linear amplifiers 44, the DC power supplies 46 have floating outputs producing voltages defined between first and second output terminal 45 and 47 respectively. The DC power supplies 46 do not have inputs, in the sense of the linear amplifiers 44, but receive an activation and polarity signal which determines the polarity of the output voltage produced across the terminals 45 and 47 of the DC power supply 46, or, in one embodiment to be described below, selects from one of several discrete output voltage values.

Detailed Description Paragraph Right (9):
As mentioned, the two linear amplifiers 44 and the pair of DC power supplies 46 are connected in series across the gradient coil 22. The linear amplifiers 44 and DC power supplies 46 are also paired symmetrically about a ground point 48 so as to drive the gradient coil 22 symmetrically about that ground point 48. This arrangement serves to minimize the voltage swing between any part of the gradient coil 22 and the ground, during the driving of the gradient coil 22, and thus reduces the effects of capacitive coupling between the gradient coil 22 and objects such as the patient 18 or the superconducting magnet which are at fixed voltage with respect to ground. Each DC power supply 46 receives the same input 43 and each linear amplifier 44 receives the same activation and polarity signal to provide this symmetry.

Detailed Description Paragraph Right (10):
A current sensing resistor 50 is inserted in series between one linear amplifier 44 and the ground point 48 to provide a voltage drop indicative of the current flow through the series connected DC power supplies 46, linear amplifiers 44 and gradient coil 22. The value of resistor 50 is sufficiently low so as not to substantially effect the symmetrical application of voltage to the gradient coil 22 as described above. The purpose of the current sensing resistor 50 is to provide an indication on

line 56 of the actual gradient field produced. As such, it will be understood to those of ordinary skill in the art that other current sensors may be used including those from Hall effect transducers or DC transformers.

Detailed Description Paragraph Right (11):
The series connection of the DC power supplies 46 and the linear amplifiers 44, as described above, combines the advantages of each power source. The linear amplifiers 44 provide accurate and continuous regulation of the current through the gradient coil 22, particularly needed during the periods of collection of the NMR data, while the DC power supplies provide a relatively inexpensive and reliable source of high voltage necessary to rapidly switch the gradient currents against the inductive load of the gradient coil 22. The linear amplifiers 44 serve to "fill-in" for voltage values between those provided by the DC power supplies 46 and to effectively regulate the combined voltage as will be described below.

Detailed Description Paragraph Right (12):
The coordination of the DC power supplies 46 and the linear amplifiers 44 is provided by the combined action of an open-loop DC controller 52 and closed-loop current feedback employing summing node 54. The analog gradient signal 16, reflecting the desired current through gradient coil 22 is received both by the DC controller 52 and the summing node 54. As will be described in more detail below, based on the gradient signal 16, the DC controller 52 controls the polarity and discrete voltage of the DC power supplies 46 to provide an approximation of the necessary voltage needed to drive the required current through the gradient coil.

Detailed Description Paragraph Right (13):
A current feedback signal 56 derived from the current sensing resistor 50 is subtracted from the same gradient signal 16 to produce an error signal 58 according to conventional feedback control. This error signal 58 represents the difference between the current Ig through the gradient coil 22 and the desired current as indicated by the gradient signal 16. This error signal 58, after passing through gain block 59, is input to the linear amplifiers 44. The gain block provides the necessary signal amplification and compensation to satisfy amplifier stability criteria such as are understood in the art. The linear amplifiers 44 provide a voltage output supplementing that of the DC power supplies 46 and modifying the current flow through the gradient coil 22 to reduce the error signal 58 to zero. The error signal 58 thus brings the current Ig through the gradient coil to the desired value reflected in the gradient signal 16.

Detailed Description Paragraph Right (14):
Thus, the DC power supplies 46 are controlled directly by the gradient signal 16 without regard to the actual current flowing through the gradient coil 22, and the linear amplifiers 44 are controlled by the actual current flowing through the gradient coils 22 to make up whatever difference is required to bring that current to the proper level. The linear amplifiers 44 sense the gradient coil current through feedback resistor 50.

Detailed Description Paragraph Right (15):
In order that the two sources of gradient power, the DC power supplies 46 and the amplifiers 44, operate effectively together, the unit of voltage which may be applied to the gradient coil 22 by each DC power supply 46 is limited to a value less than the maximum output voltage of the linear amplifier 44. This ensures that the combination of the linear amplifiers 44 and the DC power supplies 46 can provide a continuously varying controlled voltage anywhere within a range from zero volts to a maximum equal to the sum of the maximum output voltages of the linear amplifiers 44 and DC power supplies 46.

Detailed Description Paragraph Right (16):
Referring now to FIGS. 3 and 4, in a first embodiment, each DC power supply 46 includes a capacitor bank 64 which is precharged to a capacitor standby voltage by a low powered charger (not shown) measured between a positive terminal 63 and negative terminal 65. This capacitor bank 64 is connected, through a switching network 66 to the first and second terminals 45 and 47 of the DC power supply 46.

Detailed Description Paragraph Right (17):
The switching network 66 includes four power transistors 71, 72, 73 and 74, such as N-channel IGBT type devices, which are arranged to connect the capacitor bank 64 in series with the gradient coil 22 in either of two polarities, i.e. so that the first terminal 45 of the DC power supply 46 is either: 1) more positive than the second

terminal 47 (the "positive polarity") or 2) more negative than the second terminal (the "negative polarity"). The transistors 71-74 of the switching network 66 may also be controlled so as to disconnect the capacitor bank 64 from the gradient coil 22 and to connect together the first and second terminals 45 and 47 of the DC power supply 46, producing zero output voltage (the "shorted" state).

Detailed Description Paragraph Right (18):
In the network, transistors 71 and 72 are connected across the capacitor bank 64, with the collector of transistor 71 connected to the positive tern-Linal 63 of the capacitor bank 64 and its emitter connected to the collector of transistor 72 and to the first terminal 45 of the DC power supply output 46. The emitter of transistor 72 is then connected to the negative terminal 65 of the capacitor bank 64. Likewise transistors 73 and 74 are also connected in series across the capacitor bank 64, with the collector of transistor of 74 connected to the more positive terminal 63 of the capacitor bank 64 and its emitter connected to the second terminal 47 of the DC power supply 46 and to the collector of transistor 73. The emitter of transistor 73 is in turn connected to the negative terminal 65 of the capacitor bank 64.

Detailed Description Paragraph Right (19):
Each of transistors 71-74 has a diode 76 arranged to conduct current from the emitter of each transistor to its collector. It will be understood from this description that these diodes 76 thus form a full wave rectifier bridge, each leg of the bridge having one transistor 71-74 bridging that leg.

Detailed Description Paragraph Right (20):
The base of each transistor 71-74 may be biased "ON" or "OFF" to produce the negative polarity, positive polarity and shorted states described above. This biasing is shown in Table I where the letters W, X, Y and Z identify the bases of transistors 71-74 respectively.

Detailed Description Paragraph Right (21):
Thus, the switching network 66 allows the voltage of the capacitor bank 64 to be selectively applied to the gradient coil 22 to augment the voltage produced by the linear amplifiers 44. The transistors 71 through 74 operating largely either in a fully on or fully off state, consume little power (as opposed to the transistors of the linear amplifiers 44) and hence preserve the natural efficiency of the DC power supplies 46 in delivering power to the gradient coil 22.

Detailed Description Paragraph Right (22):
Referring now to FIGS. 3, 4 and 5, the DC power supplies 46 of FIG. 4 are controlled by a DC controller 52 which produces the activation and polarity signals 49 made up of base driving signals for transistors 71 through 74 as detailed in Table I.

Detailed Description Paragraph Right (23):
The DC controller 52 employs a differentiator 78, which receives the analog gradient signal 16 (indicating the desired current through gradient coil 22) and takes its derivative with respect to time. This derivative is multiplied by the impedance of the gradient coil 22 to produce an accelerating voltage 80 representing the voltage that would have to be applied to the gradient coil 22 to achieve the change in current through the gradient coil 22 dictated by the gradient signal 16. It will be understood that although the gradient coil 22 is modeled above as a simple inductance, that more complex models may readily be employed, such models including resistive and capacitive effects, the frequency dependance of the impedance, and capacitive and inductive coupling between the gradient coil 22 and the patient and magnet structure.

Detailed Description Paragraph Right (24):
This accelerating voltage 80 is received by a two-step comparator 82 which produces a positive polarity signal 84 if voltage 80 is greater than or equal to the total precharged voltage of capacitor bank 64 times the number of DC power supplies 46. The two step comparator produces a negative polarity signal 86 if voltage value 80 is less than or equal to the negative of the total precharged voltage of capacitor bank 64 times the number of DC power supplies 46. For other voltages 80, the two step comparator 82 produces neither signal 84 or 86 which indicates a shorted condition of the DC power supply 46 is desired.

Detailed Description Paragraph Right (25):
Switch logic 83 next interprets the positive and negative polarity signals 84 and 86 into base driving signals for transistors 71 through 74, of the switching networks

66, according to Table I. These base driving signals are the activation and polarity signals 49.

Detailed Description Paragraph Right (26):
Thus, if the required voltage across the gradient coil 22 is at least as great as the precharge voltage which is provided (initially) by the DC power supplies 46, the DC power supplies 46 are connected to the gradient coil 22. Incremental voltages greater or less than the precharged voltage of the capacitor bank are provided by the linear amplifiers 44.

Detailed Description Paragraph Right (27):
The capacitor bank 64 may both source and sink current to and from the gradient coil 22 so that at the conclusions of a gradient excitation, i.e., when the current through the gradient coil 22 is zero, the precharge voltage on the capacitor bank 64 is largely undiminished. The condition that the precharge voltage is undiminished strictly requires that the magnitude of the slope of the change in the gradient current be constant for changes in the gradient field. Even under these conditions, some diminution of charge occurs, however, because of the resistive component of the gradient coil 22 and other loss elements. Accordingly, the charge on the capacitor bank 64 must be augmented by some recharging of the bank from an external source. This external source may be a separate power supply, however, preferably, and if the DC power supply 46 is not sufficient alone to provide the change in gradient current, the linear amplifiers 44 are used. Restoration of the charge on capacitor bank 64, permits the assumption of a constant precharge voltage implicit in the calculation performed by the two step comparator 82 in deciding whether to switch the DC power supplies 46 into the circuit or not.

Detailed Description Paragraph Right (28):
Referring to FIG. 7(a) a gradient signal 16 may be divided into periods of constant gradient strength (hence constant current) A, D, and G and periods of transition or changing gradient strength B/C, and E/F. The derivative of the gradient signal 16, as produced by the differentiator 78 of FIG. 5, produces a voltage signal 80, shown in FIG. 7(b). The voltage signal 80 is related to the gradient signals 16, by having a value of zero for the constant periods A, D, and G and a finite magnitude for the transition periods BIC, and E/F. If the value of the voltage 80 during transition periods B/C, and E/F is sufficient, the DC controller 52 will connect the capacitor bank 64 to the gradient coil 22.

Detailed Description Paragraph Right (29):
Referring to FIG. 7(c), the voltage Vc on the capacitor bank 64, when it is connected to the gradient coil 22 at the start of a transition in periods B or E, rises toward the capacitor precharge voltage V.sub.p as the capacitor bank 64 is connected to oppose the voltage of the gradient coil 22 and receives current from the gradient coil 22. The voltage Vc on the capacitor bank 64 then peaks at points 88 as the current through the gradient coil 22 reaches zero (the energy of the gradient coil having been effectively transferred to the capacitor bank 64) and then begins to fall again as the current through the gradient coil 22 reverses direction and charge is drained from the capacitor bank 64 in periods C and F. The DC power supply 46 is then shunted so that the output voltage 91 drops to zero, however the voltage Vc on the capacitor bank 64 simply remains constant at a standby level. The difference in voltage between the capacitor precharge value Vp and the peak voltage at point 88, when gradient current is zero, represents the loss of charge in the capacitor bank 64 due to resistance of the gradient coil 22 and other loss mechanisms. This loss may be corrected, provided the voltage of the DC power supply is sufficient to handle the changes in gradient filed, by the linear amplifiers 44 by providing them with a correction signal 90, shown in FIG. 7(d) during the transition periods B/C, and E/F.

Detailed Description Paragraph Right (30):
The correction signal 90 is summed to the error current 58 prior to it being received by the inputs 43 of the linear amplifiers 44 so that the voltage Vc on the capacitor bank 64 rises faster or slower during period B or E than it falls during periods C or F.

Detailed Description Paragraph Right (31):
Specifically, the correction signal 90 comprises a triangle wave having a varying amplitude dependent on the difference between the precharge voltage Vp and the peak voltage at points 88 during the most recent transition between periods B and C, or E and F.

Detailed Description Paragraph Right (32):
Referring to FIGS. 7(d) and 7(e), the correction signal 90, when summed with the error signal 58 alters actual gradient current Ig during the transition periods B/C, and E/F slightly, modifying the gradient current Ig from that dictated by the gradient signal 16. Nevertheless, it has been determined that this slight modification of the gradient waveform during transition periods B/C and E/F is acceptable in its effect on the fidelity of the produced NMR image and of no effect for many imaging techniques where NMR data is only taken during periods of constant gradient value A, D and G.

Detailed Description Paragraph Right (33):
Referring again to FIG. 7(c), as the peak voltage at point 88 approaches the desired precharge voltage Vp of the capacitor bank 64, the triangle wave of the correction signal 90 decreases in amplitude so that the capacitor peak voltage 88 asymptotically approaches the desired precharge voltage Vp.

Detailed Description Paragraph Right (34):
The capacitor precharge voltage Vp, as mentioned, affects the proper switching point of the DC power supplies 46 into the circuit as controlled by the two step comparator 82. Nevertheless, the inherent correction action of the feedback loop of linear amplifiers 44 reduces the importance of precisely regulating the capacitor peak voltage to equal the desired precharge voltage Vp.

Detailed Description Paragraph Right (35):
Referring to FIG. 6, the correction signal 90 is produced by a triangle generator 92 generating the above described triangular waveform during transition periods B/C, and E/F. The capacitor voltage Vc on line 89 is sampled during the transition times of the gradient current Ig and compared to a reference supply 99 indicating the desired level of the capacitor precharge voltage Vp. The zero crossing signal 97 also provides polarity information to the triangle generator 92 to produce the proper polarity of triangle wave to correspond to the gradient signal 16 as shown in FIG. 7(a) and (d).

Detailed Description Paragraph Right (37):
Referring now to FIG. 8, in a second embodiment, the capacitor bank 64 is replaced with three series connected DC sources 94, 96 and 98 together to provide a voltage across terminals 63' and 64', where terminal 63' is the more positive terminal of the two. Each DC source 94-98 provides either a positive voltage weighted according to a binary weighting scheme or a shorted state of zero voltage. In the shorted state, the DC voltages 94-98 present a zero resistance across their terminals to transmit the voltage of the other series connected sources. Thus, combinations of the DC sources 94-98 either at their positive voltage values or shorted may produce a range of equally stepped voltages from zero to the sum of their positive voltages. The DC sources 94-98 are conventional "four quadrant" floating power supplies having transistors which disconnect their outputs from power and short those output when they are in the shorted state.

Detailed Description Paragraph Right (38):
The weighting of the DC sources 94-98 is such that the voltage of DC source 96 is twice that of DC source 94 and the voltage of DC source 98 is four times that of the DC source 94. The DC power supply 46 may thus produce not one but eight equally spaced discrete voltage levels and, by means of switching network 66, two polarities. Nevertheless, the DC power supply 46 using the DC sources 94-98 still produces a discontinuous output which must be corrected to conform to the precise gradient signal 16 by the linear amplifiers 44.

Detailed Description Paragraph Right (39):
Referring to FIG. 9, the control of the DC sources 94-98 of FIG. 8 is accomplished by a modified DC controller 52 receiving the analog gradient signal 16. The gradient signal 16 is again differentiated by differentiator 78 and multiplied by the inductance of the gradient coil 22 to produce an accelerating voltage 80.

Detailed Description Paragraph Right (40):
The voltage 80, which is equal to the voltage that must be applied across the gradient coil 22 to achieve the desired gradient current, is received by a three bit analog-to-digital converter 100. The analog-to-digital converter 100 converts the voltage 80 into a three bit digital word 102, one bit of which controls each of the DC sources 94-98. Specifically, one bit of the three bit word 102 is connected to

one of the three DC sources 94-98 with the most significant bit of the three bit word 102 controlling DC source 98. Each DC source 94-98 provides a shunted zero volt output when corresponding bit of word 102 is in the "false" state and a positive voltage output when the corresponding bit of word 102 is in the "true" state.

Detailed Description Paragraph Right (41):
The analog-to-digital converter 100 also produces polarity signals 84 and 85 to control the switching network 66, and indicating whether the voltage 80 is greater than or less than zero volts. Such polarity signals driving switch logic 83, as before, to control the switching network 66 of the DC power supply 46.

Detailed Description Paragraph Right (42):
FIG. 10 shows another embodiment of a gradient amplifier system 42 similar to that shown in FIG. 3 except the latter embodiment utilizes a single linear amplifier 44 having its outputs connects directly to each of the DC power supplies 46. In that embodiment, the current sensing resistor 50 has been eliminated and the current feedback signal 56 is produced by a high voltage current sensor 110 connected in series with the gradient coil 22.

Detailed Description Paragraph Right (43):
In other embodiments, the linear amplifiers 44 can be replaced by one or two switchmode amplifiers operating at a relatively high switching frequency. For example, the DC power supplies 46 operate at a frequency of one KHz and the switchmode amplifiers operate at 500 KHz so that ripples of his frequency do not interfere with the high speed sampling of the MRI signals emitted by object 18.

Detailed Description Paragraph Right (44):
FIG. 11 shows one such embodiment of the gradient amplifier system 42 which utilizes a pair of switchmode amplifiers 112 connected in series between the two high voltage DC power supplies 46, in place of the two linear amplifiers 44 in the embodiment of FIG. 3. Each of the switchmode amplifiers 112 has a structure similar to that of each of the high voltage DC power supplies 46 described previously. The version of the switchmode amplifiers 112 illustrated in FIG. 11 represents the simplest embodiment in that the amplifiers 112 are capable of only three voltage outputs: zero volts and a predetermined voltage of either of two polarities. The selection of the voltage output from the switchmode amplifiers 112 is determined by four binary switching signals on bus 114 which are similar to the binary signals applied to the bases W-Z of the transistors in each of the high voltage DC power supplies 46, as described above.

Detailed Description Paragraph Right (45):
Each of the switchmode amplifiers 112 includes a switching network having four N channel IGBT type power transistors 116-119 which are arranged to connect the output of a low voltage power supply 120 in series with the gradient coil 22 in either of two polarities. For example, the low voltage power supply 120 produces an output of 300 volts, whereas the high voltage supplies 46 have maximum outputs of 600 volts. The positive and negative terminals 122 and 124 respectively of the low voltage power supply 120 may be alternately connected to either a terminal of the high voltage power supply 46 or to a ground node 48 between the two switchmode amplifiers 112.

Detailed Description Paragraph Right (46):
Specifically, transistors 116 and 117 are connected across the low voltage power supply 120 with the collector of transistor 116 being connected to the positive terminal 122 and its emitter is connected to the collector of transistor 117. Node 125 at the emitter of transistor 116 in one switchmode amplifier is connected to terminal 47 of one of the high voltage DC power supplies 46, whereas node 125 at the emitter of transistor 116 in the other switchmode amplifier is connected to ground node 48. The emitter of transistor 117 is connected to the negative terminal 124 of the low voltage power supply 120. Likewise, transistors 118 and 119 are also connected in series in the same manner across the output terminals 122 and 124 of the low voltage power supply 120. The node 126 between transistors 118 and 119 in one switchmode amplifier 112 is connected to the ground node 48, whereas the same node 127 in the other switchmode amplifier is connected to terminal 45 of the other high voltage DC power supply 46.

Detailed Description Paragraph Right (47):
Each of the transistors 116-119 has a diode 128 arranged to conduct current from the emitter to the collector of the transistor. It will be understood from this

description that the diodes 128 form a full-wave rectifier bridge, each leg of the bridge having one transistor 116-119 bridging that leg.

Detailed Description Paragraph Right (48):
The base of each transistor 116-119 may be biased "on" or "off" to produce the negative polarity, positive polarity or shorted states described above with respect to the DC power supplies 46. The biasing of the transistors is determined by control circuit 30 comparing the sensed current feedback signal 56 to the desired current level and driving the switchmode amplifiers to achieve the desired current. This biasing is shown in Table I above where the letters J-M identify the bases of transistors 116-119, respectively. Thus, the switching network formed by transistors 116-119 and diodes 128 allows the output of the low voltage power supply 120 to be selectively applied to the gradient coil 22. The transistors 116-119 operating, basically either in the fully on or fully off state, consume little power and hence preserve the natural efficiency of the low voltage power supply 120 in delivering power to the gradient coil 22. The bases J-M of the four transistors 116-119 in each of the switchmode amplifiers 112 are coupled to a control circuit 130 by a parallel signal bus 114 in much the same way as the high voltage DC power supplies 46 have the bases of their transistors connected to the control circuit.

Detailed Description Paragraph Right (49):
FIG. 11 illustrates a current sensor 110 connected in series with the gradient coil 22 to provide a coil current feedback signal 56 to the control circuit 130. Alternatively, a current sensing resistor may be connected between the ground node 48 and node 126 of one of the switchmode amplifiers 112 to provide a current feedback signal to the control circuit 130, in a similar manner to that shown with respect to the embodiment in FIG. 3.

Detailed Description Paragraph Right (50):
Control circuit 130 responds to the analog gradient signal and current feedback signal 56 by controlling the states of the transistors to produce the appropriate voltage for gradient coil 22. In a similar manner to that described above by which the transistors in the high voltage power supply 46 are switched, control signals are applied by the control circuit via bus 114 to switch the transistors 116-119 in each of the switchmode low voltage amplifiers 112.

Detailed Description Paragraph Right (51):
FIG. 12 illustrates another version of the gradient amplifier system 42 which utilizes a single switchmode amplifier 112 in series with the two high voltage DC power supplies 46 to furnish voltage to gradient coil 22. The single switchmode amplifier 112 in this embodiment switches the output from a series connected pair of low voltage power supplies 120 to the terminals 45 and 47 of the high voltage DC power supplies 46. The operation of the single switchmode amplifier 112 is similar to that described above with respect to the dual switchmode amplifier version in FIG. 11. Specifically, a control circuit 130 generates a set of transistor switch control signals that are applied to the bases J-M of the transistors 116-119 in the switching network.

Detailed Description Paragraph Right (52):
With reference to FIG. 13, the gradient amplifier can utilize four high voltage switchmode amplifiers 141, 142, 143 and 144. Each of the four switchmode amplifiers 141-144 is similar to the ones shown in FIG. 11 and described previously. The first and second switchmode amplifiers 141 and 142 have lower voltage power supplies 151 and 152 as compared to the power supplies 153 and 154 in the third and fourth switchmode amplifiers 143 and 144. For example, high voltage power supplies 151 and 152 produce 250 volts DC across their output terminals and high voltage power supplies 153 and 154 produce 750 volts DC across their output terminals.

Detailed Description Paragraph Right (53):
Node 126 of the first switchmode amplifier 141 is connected to node 125 of the second switchmode amplifier 142 by a pair of linear amplifiers 146 and 148 with their outputs connected in series between the nodes. Linear amplifier 146 has an input coupled to the output a control circuit 150 which receives the analog gradient signals 16. The other linear amplifier 147 is connected in a master/slave relationship to linear amplifier 146. Node 125 of the first switchmode amplifier 141 is connected to node 126 of the third first switchmode amplifier 143 which has its node 125 connected to the gradient coil 22. Node 126 of the second first switchmode amplifier 142 is connected to node 125 of the fourth first switchmode amplifier 144 which has its node 126 connected to the gradient coil 22 via the current sensor 110.

Detailed Description Paragraph Right (54):
The bases of the transistors within the switchmode amplifiers 141-144 are biased "ON" or "OFF" by control signals N, P, Q, R, S, T, U or V to produce the negative polarity, positive polarity and shorted states described above with respect to the embodiment in FIG. 11. Specifically the switching of the transistors in the first and second switchmode amplifiers 141 and 142 is controlled by signals N, P, Q and R produced by the control circuit 150. Similarly the control circuit 150 produces signals S, T, U and V to control the transistors in the third and fourth switchmode amplifiers 143 and 144.

Detailed Description Paragraph Right (55):
The above description has been that of preferred embodiments of the present invention. It will occur to those who practice the art that many modifications may be made without departing from the spirit and scope of the invention. For example, it will be understood from the above discussion that the symmetrical driving of the gradient coil 22 is not essential to the invention but that non-symmetrical configurations may be employed. In such non-symmetrical configuration, a single linear amplifier and DC power supply may be used. Or, multiple power supplies and amplifiers may be used and controlled with different signals to produce a non-symmetrical driving of the gradient coil. Further, the DC sources 94-98 may each include separate capacitor banks 64 so as to both generate and receive gradient current. In order to apprise the public of the various embodiments that may fall within the scope of the invention, the following claims are made.

Detailed Description Paragraph Center (2):
MRI System Hardware

Detailed Description Paragraph Center (3):
Gradient Amplifiers

CLAIMS:

1. An amplifier for a gradient oil of a magnetic resonance imaging system, the amplifier receiving a gradient signal and producing voltage to generate a gradient current in a gradient coil to produce a desired magnetic gradient field, the amplifier comprising:

a DC power supply having an input for receiving the gradient signal and having an output connected to the gradient coil for impressing a first voltage component across the gradient coil, the first voltage component being selectable from a discontinuous range of output voltages and approximating the voltage needed to produce the gradient current;

a feedback sensor connected to the gradient coil for producing a feedback signal indicative of a magnetic gradient field produced by the gradient coil; and

an amplifier device having an output connected to the gradient coil for impressing a second voltage component across the gradient coil, the second voltage component being within a continuous range of output voltages, and having an input receiving the feedback signal and the gradient signal to adjust the second voltage component so that the sum of the first and second voltage components generates the gradient current in the gradient coil to produce the desired magnetic gradient field.

2. The amplifier as recited in claim 1 wherein the DC power supply has more than one DC source with each DC source being switchable to produce incremental voltage or zero voltage, such DC sources being connected so that the sum of the incremental voltages defines the discontinuous range of output voltages and so that the first voltage component is the sum of only the incremental voltages from those DC sources that are switched to produce an incremental voltage.

3. The amplifier as recited in claim 2 wherein the incremental voltages for each DC source differ in value between each DC source according to a binary relationship.

4. The amplifier as recited in claim 1 wherein the feedback sensor is a resistor connected in series with the gradient coil to generate a voltage proportional to the gradient current and hence to the gradient magnetic field.

5. The amplifier as recited in claim 1 wherein the DC power supply is a precharged capacitor which may be connected to or disconnected from the gradient coil to generate either a first voltage component or zero voltage.

6. The amplifier as recited in claim 5 comprising:

a source of a reference signal that indicates a desired peak capacitor voltage; and

an error voltage generator having a first input for receiving the reference voltage, a second input for receiving a signal representing a voltage on the capacitor, and an output coupled to the amplifier device for altering the second voltage component to move a peak voltage across the capacitor toward the desired peak capacitor voltage.

7. The amplifier as recited in claim 6 wherein the error voltage generator is gated to produce the third voltage component only during changes in the gradient current caused by changes in the first or second voltage components.

8. In a magnetic resonance imaging system, an apparatus which receives a gradient current signal and produces a corresponding gradient current in a gradient coil to generate a desired magnetic gradient field, the apparatus comprising:

a differentiator for differentiating the gradient current signal to produce a driving voltage signal;

a DC power supply having an output connected to the gradient coil for impressing, across the gradient coil, a first voltage component that is selectable from a discontinuous range of output voltages;

a digitizer for receiving the driving voltage signal and connected to the DC power supply to produce a digital switching signal to select the first voltage component from the discontinuous range of output voltages to approximate the voltage needed to generate the gradient current;

a feedback sensor connected to the gradient coil for producing a feedback signal indicative of the gradient current; and

an amplifier having an output connected to the gradient coil for impressing a second voltage component across the gradient coil, the second voltage component being within a continuous range of output voltages, and the amplifier receiving and responsive to the feedback signal and the gradient signal by adjusting the second voltage component so that the sum of the first and second voltage components generates the gradient current in the gradient coil to produce the desired magnetic gradient field.

9. An apparatus for receiving a gradient signal and producing voltage to generate a current in a gradient coil of a magnetic resonance imaging system, the apparatus comprising:

a controller which produces first and second control signals from the gradient signal;

a first DC power supply having an input connected to said controller for receiving the first control signal and having first and second output terminals across which is produced a first voltage component having a magnitude adjustable in response to the first control signal, and the first output terminal being coupled to the gradient coil;

a second DC power supply having an input connected to said controller for receiving the first control signal and having third and fourth output terminals across which is produced a second voltage component having a magnitude adjustable in response to the first control signal, and the fourth output terminal being coupled to the gradient coil; and

an amplifier assembly responsive to the second control signal by producing a third voltage component at an output that is connected between the second and third terminals of said first and second DC power supplies, so that the sum of the first, second and third voltage components generates the current in the gradient coil to produce the desired magnetic gradient field.

10. The apparatus as recited in claim 9 wherein at least one of said first and second DC power supplies has more than one DC source, each such DC source being switchable to produce an incremental voltage or zero voltage, the DC sources connected so that the sum of the incremental voltages define a range of output voltages and so that the corresponding first or second voltage component is the sum of only the incremental voltages from those DC sources that are switched to produce an incremental voltage.

11. The apparatus as recited in claim 10 wherein the incremental voltages for each DC source differ in value between each DC source in according to a binary relationship.

12. The apparatus as recited in claim 9 wherein each one of said first and second DC power supplies comprises:

a source of a DC voltage;

four diodes connected as a full wave rectifier bridge having positive and negative nodes connected to said source of a DC voltage and having another pair of nodes which are connected to the output terminals of said DC power supply; and

four switch elements each being connected across one of said diodes and being rendered conductive in response to the second control signal.

14. The apparatus as recited in claim 9 wherein said amplifier assembly comprises a pair of linear amplifiers with outputs connected in series between the second and third terminals of said first and second DC power supplies.

15. The apparatus as recited in claim 14 wherein said amplifier assembly further comprises a current sensing resistor coupling the outputs of said pair of linear amplifiers, one end of said resistor being connected to ground and another end of said resistor being coupled to said controller to provide a signal indicative of a magnitude of current flowing through the gradient coil.

16. The apparatus as recited in claim 9 wherein said amplifier assembly comprises a single linear switchmode amplifier having a DC source that produces the third voltage component.

17. The apparatus as recited in claim 9 wherein the third voltage component is less than each of the first and second voltage components.

18. The apparatus as recited in claim 9 wherein said amplifier assembly includes a pair of switchmode amplifiers with outputs connected in series between the second and third terminals of said first and second DC power supplies.

19. The apparatus as recited in claim 18 wherein each of said switchmode amplifiers comprises:

a source of DC voltage which is less than each of the first and second voltage components;

a set of four diodes connected as a full wave rectifier bridge having positive and negative nodes connected to said DC voltage source and having another pair of nodes which form the output said switchmode amplifier; and

four switch elements each being connected across one of the diodes in said set and being rendered conductive in response to the second control signal.

20. The apparatus as recited in claim 9 wherein said first and second DC power supplies select the first and second voltage components, respectively, from a group of voltage levels in response to the first control signal.

21. An apparatus for receiving a gradient signal and producing voltage to generate a current in a gradient coil of a magnetic resonance imaging system, the apparatus comprising:

a first DC power supply having an input for receiving a first control signal and having first and second output terminals across which is produced a first voltage

component selectable from a group of voltage levels in response to the first control signal, and the first output terminal being coupled to the gradient coil;

a second DC power supply having an input for receiving the first control signal and having third and fourth output terminals across which is produced a second voltage component selectable from a group of voltage levels in response to the first control signal, and the fourth output terminal being coupled to the gradient coil;

a switchmode amplifier assembly responsive to a second control signal by producing a third voltage component at an output that is connected in series between the second and third output terminals of said first and second DC power supplies, so that the sum of the first, second and third voltage components generates the current in the gradient coil to produce the desired magnetic gradient field; and

a controller which produces the first and second control signals from the gradient signal, and being connected to said switchmode amplifier assembly and to said first and second DC power supplies.

22. The apparatus as recited in claim 21 wherein said switchmode amplifier assembly comprises:

a first source of DC voltage which is less than each of the first and second voltage components;

a first set of four diodes connected as a full wave rectifier bridge having positive and negative nodes connected to said first source of DC voltage and having first and second output nodes; and

a first quartet of switches with each switch being connected across a different diode in said first set, and being rendered conductive in response to the second control signal.

23. The apparatus as recited in claim 22 wherein said switchmode amplifier assembly further comprises:

a second source of DC voltage which is less than each of the first and second voltage components;

a second set of four diodes connected as a full wave rectifier bridge having positive and negative nodes connected to said second source of DC voltage, and having third and fourth output nodes with the third node being coupled to the second node; and

a second quartet of switches with each being connected across a different diode in said second set, and being rendered conductive in response to the second control signal.

24. An apparatus for receiving a gradient signal and producing a voltage to generate a current in a gradient coil of a magnetic resonance imaging system, the apparatus, said apparatus comprising:

a controller which produces first and second control signals and an analog signal from the gradient signal;

a first DC power supply having an input connected to said controller for receiving the first control signal and having first and second output terminals across which is produced a first voltage component selectable from a plurality of voltage levels in response to the first control signal, and the first output terminal being coupled to the gradient coil;

a second DC power supply having an input connected to said controller for receiving the second control signal and having third and fourth output terminals across which is produced a second voltage component selectable from a group of voltage levels in response to the first control signal, and the third output terminal being coupled to the second output terminal of said first DC power supply;

a third DC power supply having an input connected to said controller for receiving the first control signal and having fifth and sixth output terminals across which is produced a third voltage component selectable from a plurality of voltage levels in

response to the first control signal, and the fifth output terminal being coupled to the gradient coil;

a fourth DC power supply having an input connected to said controller for receiving the second control signal and having seventh and eighth output terminals across which is produced a fourth voltage component selectable from a group of voltage levels in response to the second control signal, and the seventh output terminal being coupled to the sixth output terminal of said third DC power supply; and

a pair of linear amplifiers which respond to the analog signal by producing a fifth voltage component across at a pair of terminals connected between the fourth and eighth output terminals of said second and fourth DC power supplies, so that the sum of the first, second, third, fourth and fifth voltage components generates the current in the gradient coil to produce the desired magnetic gradient field.

25. The apparatus as recited in claim 24 wherein each one of said first, second, third and fourth DC power supplies comprises:

a source of a DC voltage;

four diodes connected as a full wave rectifier bridge having positive and negative nodes connected to said source of a DC voltage and having another pair of nodes which are connected to the output terminals of one of said first, second, third and fourth DC power supplies; and

four switch elements each being connected across one of said diodes and being rendered conductive in response to a control signal from said controller.

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L18: Entry 1 of 1 File: USPT Apr 11, 1989

DOCUMENT-IDENTIFIER: US 4820986 A
TITLE: Inductive circuit arrangements

Abstract Paragraph Left (1):
A switched coil arrangement is connected in a bridge configuration of four switches S.sub.1, S.sub.2, S.sub.3 and S.sub.4 which are each shunted by diodes D.sub.1, D.sub.2, D.sub.3 and D.sub.4 so that current can flow in either direction through a coil L depending on the setting of the switches. A capacitor C is connected across the bridge through a switch S.sub.5 to receive the inductive energy stored in coil L on breaking the current flow path through the coil. The electrostatic energy stored in capacitor C can then be used to supply current through the coil in the reverse direction either immediately or after a time delay. Coil L may be a superconductive coil. Losses in the circuit can be made up by a trickle charge of capacitor C from a separate supply V.sub.2.

Brief Summary Paragraph Right (1):
This invention relates to inductive circuit arrangements and is concerned with arrangements which enable the current flow through an inductive coil to be rapidly switched on and off or reversed.

Brief Summary Paragraph Right (2):
In many applications of nuclear magnetic resonance (NMR) it is often required to switch on or off or to reverse magnetic fields and especially magnetic gradient fields and to effect such switching or reversal as rapidly as possible. Switching of magnetic gradient fields is important in NMR imaging applications especially where high speed is required. An example of such an application is in the echo planar imaging (EPI) technique as described in British Pat. No. 1,596,160. In EPI there is a requirement to switch trapezoidal gradient fields with a switching time of around 25 .mu.s for best effect. These gradient fields are created by passing electrical currents through inductive coil arrangements which may have non-zero resistance. For low resolution imaging low currents and small coil assemblies can be utilised and it is possible to use linear amplifiers to achieve the required switching rates and gradient amplitudes. However if high resolution is required larger gradient fields must be employed and to achieve the required high switching rates extremely high power amplifiers are necessary. It is believed that this is one of the major obstacles to the commercial development of ultra high-speed NMR imaging techniques like EPI.

Brief Summary Paragraph Right (3):
The power requirements for the rapid switching of current through an inductance will be appreciated from a consideration of the theoretical background. Let a step voltage V be applied to an inductance L through a resistor r then the size of current i is given by the well known expression

Brief Summary Paragraph Right (4):
Linear amplifiers with both high voltage and high current capability are not readily available but in any event are an inefficient and uneconomic approach for gradient switching.

Brief Summary Paragraph Right (5):
For superconductive coils, r=0 so that .tau..fwdarw..infin., equation (3). In this case, it would take an infinite time (in practice a long time) to establish any current through L. But having established a current, no power would be required to maintain it.

Brief Summary Paragraph Right (6):
It is an object of the invention to provide an inductive circuit arrangement the switching of which requires minimal power.

Brief Summary Paragraph Right (7):
According to the invention an inductive circuit arrangement comprises four switches connected in a bridge configuration, current supply terminals to opposite ends of the bridge, inductive coil means connected across the bridge so that current can flow in either direction through the coil means depending on the setting of the switches, a series connection of capacitor means and a switch connected across the supply terminals, and means for operating the said switches so as to connect the capacitor means across the coil means at least for a sufficient period of time until the current flow through the coil reduces to zero by charging of the capacitor means.

Brief Summary Paragraph Right (8):
In carrying out the invention the said means for operating the switches may function subsequently to allow the capacitor means to discharge to generate current flow through the coil means in the opposite direction to the initial flow.

Brief Summary Paragraph Right (9):
Preferably the said switches are shunted by unidirectional current flow devices.

Brief Summary Paragraph Right (10):
It will be seen that in the operation of the above circuit arrangement the magnetic energy stored in the inductive coil is not destroyed but is transformed to electrostatic energy for storage in the capacitor means. Thus the power required to switch or reverse the current through the coil is theoretically zero since the total energy of the system comprising coil and capacitor is constant. In practice there will be minor energy losses but these can be compensated for by provided trickle charge means connected to the capacitor means to enable the capacitor means to be charged to a predetermined voltage value after discharge. It is desirable to ensure that the said predetermined voltage is greater than the voltage across the supply terminals.

Brief Summary Paragraph Right (11):
It may be desirable to connect a unidirectional current flow device in series with the current supply terminals to prevent flow of current through the current supply terminals in the reverse direction.

Brief Summary Paragraph Right (13):
To provide start-up energy for the circuit initiating charge means comprising an additional power supply can be connected through a switch to initially charge the capacitor means to a peak voltage to provide the requisite electrical energy to establish the required current flow in the said coil means.

Brief Summary Paragraph Right (14):
It may also be desirable to provide a switched parallel path across the bridge to maintain a substantially constant value of current through the current supply terminals irrespective of the settings of the switches in the bridge configuration.

Brief Summary Paragraph Right (15):
In one embodiment of the invention the bridge configuration is so modified that the two arms of the bridge are connected to different current supply terminals and separate series connections each of a capacitor means and a switch are connected to each supply terminal so as to enable different values of current flow to be established through the coil in respective opposite directions.

Brief Summary Paragraph Right (16):
In certain embodiments of the invention the capacitor means is used as a temporary energy store only and a second inductive coil means is provided as a more long-term store. Such an arrangement is useful where immediate current reversal in an operating coil is not required. In one such embodiment a further bridge configuration with associated further current supply terminals is provided with a further inductive coil means connected across the said further bridge configuration and the capacitor means is also connected in series with a further switch across the further current supply terminals. With such an arrangement the energy in the operating coil is first transferred to the capacitor means in the manner described

above and is then transferred to the further inductive coil means where it can be stored indefinitely, with any losses if need be being made up from the voltage source connected across the further current supply terminals.

Brief Summary Paragraph Left (5):
For very low winding resistance, this power can be made arbitrarily low. However, for a given value of inductance L and rise time, equation (5) determines the peak power requirements of the driver amplifier. For linear amplifiers this situation presents something of a dilemma. Peak powers and voltages exceeding the capability of the amplifier may be required for short durations only, in order to establish the steady state current I. Then according to equation (6), the power requirement may drop to an arbitrarily low figure, though I may be high.

Drawing Description Paragraph Right (5):
FIG. 4 is a circuit embodying the invention for enabling opposite current flows in a coil to have different amplitudes,

Drawing Description Paragraph Right (6):
FIG. 5 illustrates various current waveforms possible by using the invention,

Drawing Description Paragraph Right (7):
FIG. 6 illustrates an embodiment of the invention in which two inductive coils are used,

Drawing Description Paragraph Right (8):
FIG. 7 illustrates another embodiment of the invention in which a second coil is used for energy storage, and

Drawing Description Paragraph Right (9):
FIG. 8 is an embodiment of the invention utilising solid state switches.

Detailed Description Paragraph Right (1):
Referring now to FIG. 1 there is illustrated therein a bridge configuration of four switches S.sub.1, S.sub.2, S.sub.3 and S.sub.4. Each switch is shunted by a respective diode D.sub.1, D.sub.2, D.sub.3 or D.sub.4. All the diodes are conductive in the same direction. An inductive coil L is connected across the bridge between points A and B. The bridge has current supply terminals T.sub.1 and T.sub.2, terminal T.sub.2 being earthed and terminal T.sub.1 being supplied from a voltage or current supply V.sub.1 through a diode D.sub.6. A series connection of a capacitor C and switch S.sub.5 is connected across the bridge between terminals T.sub.1 and T.sub.2 and switch S.sub.5 is shunted by a diode D.sub.5. Capacitor C can be charged from a voltage supply V.sub.2 through a diode D.sub.7 and resistor R.sub.1. The various switches S.sub.1 to S.sub.5 are controlled by signals applied along lines G.sub.1 to G.sub.5 respectively.

Detailed Description Paragraph Right (2):
To understand the operation of the circuit shown in FIG. 1 let it be assumed initially that switches S.sub.1 and S.sub.4 are closed and that switches S.sub.2 and S.sub.3 are open. With this arrangement of the switches current will flow through coil L from terminal A to terminal B. If now at a time t=0 switches S.sub.1 and S.sub.4 are switched off simultaneously the magnetic field in coil L will collapse and will generate an emf across the coil and by Lenz's law point A will be negative with respect to point B. Point A is clamped to earth terminal T.sub.2 through diode D.sub.3 and since point B is therefore positive there will be a continuous path for the current flowing in coil L through diodes D.sub.2 and D.sub.3, diode D.sub.5 and capacitor C. The energy in coil L will therefore be dumped into capacitor C where it will be stored as electrostatic energy. While this charging of capacitor C takes place switches S.sub.2 and S.sub.3 can be closed but the timing of their closure is not critical since current is flowing during this time through diodes D.sub.2 and D.sub.3. Switch S.sub.5 is also closed during this time without affecting the operation of the circuit. The current through coil L reaches zero at a time t=t.sub.s at which instant capacitor C becomes fully charged to a peak value of voltage V.sub.c. The time t.sub.s is defined by

Detailed Description Paragraph Right (3):
Neglecting the forward diode resistance, the total energy initially in the inductor at time t=0 is transferred to the capacitor, i.e.

Detailed Description Paragraph Right (4):

The voltage V.sub.A across the terminals T.sub.1 and T.sub.2 and the current i.sub.L through coil L are shown in FIG. 2(b) and FIG. 2(c) respectively. Prior to reversal, V.sub.A .perspectiveto.V.sub.1 and i.sub.L =I. At time t=t.sub.s, i.sub.L =0 and V.sub.A =V.sub.c. The diode D.sub.6 protects the low voltage power supply during the switching operation and allows a smooth transition back to V.sub.1 following current reversal. Since D.sub.1 conducts when S.sub.1 is switched off, a smooth transition from I to -I obtains, with no discontinuous glitches at the zero-crossing.

Detailed Description Paragraph Right (5):
The voltage V.sub.2 is variable and serves to make good energy losses in the system due to finite diode and switch resistances.

Detailed Description Paragraph Right (6):
As described the switch works with superconductive coils.

Detailed Description Paragraph Right (7):
The operation of the circuit of FIG. 1 assumed an initial steady state current flowing in the coil. However, from FIG. 2 it can be seen that at time t=t.sub.s, i.sub.L =0. That is to say, the circuit is switched off. The conditions to switch on from i.sub.L =0 are therefore those indicated, namely V.sub.c =V.sub.c. In order to achieve this, the circuit as it stands must be cycled prior to actual operation to establish the correct working voltages. However, capacitor C will not hold its charge indefinitely and V.sub.c will slowly decay from V.sub.c to V.sub.1 due to leakage resistance. Typical leakages allow V.sub.c to be held for up to 100 ms without problem.

Detailed Description Paragraph Right (8):
To avoid droop, the circuit of FIG. 1 must be modified to take an additional power supply which acts as an initiating charge means and is capable of supplying the full peak voltage V.sub.c to capacitor C. This modification is sketched in FIG. 3, in which a supply voltage V.sub.3 equal in magnitude to peak voltage VC is connected to capacitor C via a switch S.sub.6. Switch S.sub.6 is kept on when all other switches are off, that is, between pulse sequences and ensures that the requisite electrical energy is stored in capacitor C to establish the required current flow in coil L when desired. As soon as current is required through coil L, S.sub.6 is switched off, S.sub.5 is switched on and the bridge is activated. Discharge of capacitor C through the bridge immediately establishes the required magnitude of current flow in coil L. Once current is established, the operations continue as previously described. On final switch off, V.sub.3 is again coupled to capacitor C via switch S.sub.6.

Detailed Description Paragraph Right (9):
The fact that S.sub.1 to S.sub.4 are initially all off means that the load on supply V.sub.1 changes and voltage V.sub.A varies. This may be obviated by adding a third arm to the bridge of FIG. 1. This comprises a switched load connected between terminal T.sub.1 and earth which is normally off. However, when no current through coil L is required, the third arm shunts current through diode D.sub.6 to earth thereby holding V.sub.A constant.

Detailed Description Paragraph Right (10):
In the FIG. 1 circuit the bridge configuration is shown as comprising four switches. Two of these switches, for example switches S.sub.2 and S.sub.4, may be replaced by pairs of terminals for connection to individual current supply sources which replace source V.sub.1. A duplicate of capacitor C and its associated switch S.sub.5 and bypass diode D.sub.5 is connected to the opposite end of the bridge to switch S.sub.5 and point A or B is earthed instead of terminal T.sub.2. Diodes are also included at each end of the bridge.

Detailed Description Paragraph Right (11):
In the circuit described in FIG. 1 the magnitude of the forward and reverse currents are equal. However, in some NMR applications, unequal magnitudes of current are required. The basic principles of switching described above can be adapted to this situation as indicated in FIG. 4.

Detailed Description Paragraph Right (12):
In the circuit shown in FIG. 4 like parts have like references to FIG. 1 but in FIG. 4 the two arms of the bridge comprising the switches S.sub.1 and S.sub.2 are taken to two different current supply terminals T.sub.1 and T.sub.3 supplied from voltage sources V.sub.1 and V.sub.4 of different magnitudes. Separate capacitors C.sub.1 and

C.sub.2 are connected to terminals T.sub.1 and T.sub.3 through switches S.sub.5 and S.sub.8 respectively. Terminal T.sub.1 is connected to capacitor C.sub.2 through a diode D.sub.8 and terminal T.sub.3 is connected to capacitor C.sub.1 through a diode D.sub.5 shunted by diodes D.sub.5 and D.sub.8. Capacitor C.sub.1 is trickle charged from a voltage source V.sub.2 through a protective diode D.sub.7 and resistor R.sub.1. Capacitor C.sub.2 is tricle charged from a voltage source V.sub.6 through a protective diode D.sub.10 and resistor R.sub.2.

Detailed Description Paragraph Right (13):
Let an initial current I.sub.1 flow through switch S.sub.1, coil L and switch S.sub.4. On turn-off of switches S.sub.1 and S.sub.4 capacitor C.sub.1 charges, storing the initial energy 1/2LI.sub.1.sup.2. The reverse current I.sub.2.noteq.I1 then flows through switch S.sub.2, L and switch S.sub.3 with appropriate gating, provided that the energy equivalent of 1/2LI.sub.2.sup.2 was previously stored on the capacitor C.sub.2.

Detailed Description Paragraph Right (14):
If the switching process is only seldomly repeated, the necessary peak voltages on C.sub.1 and C.sub.2 may be ensured by adding two circuit arrangements as described in FIG. 3.

Detailed Description Paragraph Right (15):
In order to present roughly constant loads to the two power supplies, V.sub.1 and V.sub.2, each half of the bridge, i.e. S.sub.1, S.sub.3 and S.sub.2, S.sub.4 can be shunted by additional current switches from both D.sub.6 and D.sub.9 to earth.

Detailed Description Paragraph Right (16):
The circuits described are capable of producing a variety of useful current waveforms. One example is a trapezoidal like burst of equal amplitude positive and negative currents with periods .tau..sub.1 and .tau..sub.2, see FIG. 5(a). A similar current waveform with unequal positive and negative currents is shown in FIG. 5(b). Since the circuits actually switch off at a zero-crossing, time delays P.sub.1 and P.sub.2 may be interposed as indicated in FIG. 5(c).

Detailed Description Paragraph Right (17):
The trapezoidal edges in all cases are cosinusoidal with a rise or fall time of t.sub.s, which is experimentally accessible. For rapid switching t.sub.s is short, but this may be lengthened as in FIG. 5(d). The circuit can also be used to generate true sinusoidal waveforms, FIG. 5(e) or mixed sinusoids, FIG. 5(f).

Detailed Description Paragraph Right (18):
Arrangements for energy storage using capacitors have been described above. This is convenient since tuned circuits naturally interconvert between magnetic and electrostatic energy. In practice equations (8) and (9) dictate the storage capacitance and the peak voltage. Assuming the components can withstand this voltage, there is still the problem of top-up provided by the supply V.sub.2 in FIG. 1, and the initiating charge provided by V.sub.3 in FIG. 3. Both arrangements require relatively high voltage power supplies and in the case of V.sub.2, the current drains can be significant. For one shot waveforms there is no problem. But with repeating waveforms, as used in EPI, HT (high tension) or even EHT (extra high tension) power supplies may be required.

Detailed Description Paragraph Right (19):
An attractive and alternative approach is to use the capacitor C as a short term energy store, transferring the energy to another storage inductance, L', placed well away from the primary coil L. A circuit arrangement is shown in FIG. 6 using two bridges and two low voltage power supplies V.sub.1 and V.sub.1 '. If L=L' then V.sub.1 .perspectiveto.V.sub.1 '. Losses in the system are made up by passing extra current through L'. The losses referred to arise from power dissipation in the diodes and switches. Long term losses in the inductance (I.sup.2 r) are made up from the power supply. In a superconductive coil, these are zero. Thus once the current I is achieved in L or L' the current would be maintained with no power consumption. Note that in this arrangement, capacitor C can be small. The rise time would be limited purely by the voltage capabilities of the switches and diodes. The storage capacitor is required to hold charge for only a short time and no top-up voltage source or high voltage start-up supply is required.

Detailed Description Paragraph Right (20):
Although a four element bridge for storage coil L' strictly speaking, is not

required, the arrangement of FIG. 6 provides a more or less constant load for supply V.sub.1 '. As in the previous circuits, the bridge for coil L should be shunted with a third arm to provide a current drain on V.sub.1 when all four switch elements of that bridge are off.

Detailed Description Paragraph Right (21):
An alternative circuit is shown in FIG. 7. In this arrangement as in FIG. 1 energy is momentarily stored in capacitor C when reversing the current direction through L. However, when it is desired to switch off all four switches S.sub.1 to S.sub.4, the magnetic energy 1/2LI.sup.2 in coil L is first transferred to coil L' via switch S.sub.9. Current through S.sub.9 is controlled by a current regulator CR. The current flow through coil L' and its energy 1/2L'I'.sup.2 in coil L' is then maintained from the same supply V. A short time before current flow in coil L is required switch S.sub.g is opened and the energy in coil L' is dumped into capacitor C thus providing the necessary initial condition for start-up. This means that the current drain is fairly constant thus avoiding transient problems in the low voltage power supply. No HT or EHT top-up supplies are needed in this arrangement.

Detailed Description Paragraph Right (22):
The various switches referred to can be bidirectional mechanical devices, bidirectional solid-state devices, e.g. FET's, standard high power transistors, SCR's, unidirectional vacuum tubes or gas filled thyratrons. All can be made to function with appropriate driving circuitry. Naturally for high speed operation, mechanical switches are not as useful.

Detailed Description Paragraph Right (23):
A practical circuit based on FIG. 1 is shown in FIG. 8. Power FET's (HEXFETS IRF130) are used as the switches S.sub.1 to S.sub.5, the integral body diode of these devices being employed for the return current paths.

Detailed Description Paragraph Right (24):
A switching time t.sub.s of 50 .mu.s was chosen in order to keep the peak capacitor voltage below the device limit of 100 V using equations (8) and (9). A capacitor of 10 .mu.F satisfies the requirements.

Detailed Description Paragraph Right (25):
Switch S.sub.5 is arranged to open between transitions after the current has settled (i.e. 2t.sub.s after the last transition) to enable the capacitor voltage to be topped up to V.sub.2 as described earlier and shown in FIG. 2(a). This switch closes during a transition, when energy is being transferred into C via S.sub.5 's body diode or via S.sub.5 itself when it has closed, and S.sub.5 remains closed until the stored energy in C has been returned to the coil at time t=2t.sub.s.

Detailed Description Paragraph Right (27):
In this arrangement there is no requirement for instantaneous switching or simultaneous switching of any of the devices. Also, there is always a current path in circuit with coil L, either via the devices or the diodes during transitions thus minimising the possibility of `glitches`.

Detailed Description Paragraph Right (28):
Series/parallel combinations of devices can be used for higher voltages and currents and for shorter transition times.

Detailed Description Paragraph Right (29):
The circuit of FIG. 8 has been used to switch a current of 20 A through a coil L of 100 .mu.H with a switching time t.sub.s of 50 .mu.s.

Detailed Description Paragraph Right (30):
More powerful switches, e.g. SCR's can be used to handle very high voltages and currents (.about.4 kV and 1000 Amps). Suitable snubber circuits may be introduced between the anodes and cathodes of the SCR's in order to prevent their retriggering.

Detailed Description Paragraph Left (1):
The current flow will reverse through the now closed switches S.sub.2, S.sub.3 and S.sub.5 and capacitor C will entirely discharge to generate a current flow of magnitude-I from B to A in the reverse direction through coil L after a time 2t.sub.s.

Detailed Description Paragraph Left (3):
the energy transfer time or switching time, t.sub.s, can be chosen by an appropriate value of C. The capacitor voltage V.sub.c during a switch, is shown in FIG. 2(a). At t=0, V.sub.c =V.sub.2. After energy transfer at t=t.sub.s, V.sub.c =V.sub.c. Capacitor C discharges in the next 1/4-cycle through closed switch S.sub.5. The discharge path is through switches S.sub.2 and S.sub.3 thereby establishing a reversed current, -I, through coil L. At the end of the discharge period, when t=2t.sub.s, V.sub.c .perspectiveto.0 and at this point in time switch S.sub.5 is opened isolating C from the circuit. Thereafter the capacitor is trickle charged through resistor R.sub.1 until V.sub.c =V.sub.2.

CLAIMS:

1. An inductive circuit arrangement comprising:

four switches connected to form four arms of a bridge configuration,

current supply terminals at opposite ends of the bridge,

inductive coil means connected across the bridge so that current can flow in either direction through the coil means depending on the setting of the switches,

a series connection of capacitor means and a series switch connected across the supply terminals, and

means for operating said four switches and said series switch so as to connect the capacitor means across the coil means at least for a sufficient period of time until the current flow through the coil reduces to zero by charging of the capacitor means and so as to isolate said capacitor means from the bridge configuration to enable current to continue to flow through the coil.

2. The arrangement as claimed in claim 1 in which the said switches are shunted by unidirectional current flow devices.

3. The arrangement as claimed in claim 1 in which the said means for operating the switches functions subsequently to the reduction of the current flow through the coil to zero to allow the capacitor means to discharge to generate current flow through the coil means in the opposite direction to the current flow in one direction.

4. The arrangement as claimed in claim 3 in which there is provided trickle charge means connected to the capacitor means to enable the capacitor means to be charged to a predetermined voltage value after discharge.

6. The arrangement as claimed in claim 1 in which a unidirectional current flow device is connected in series with the current supply terminals to prevent flow of current through the current supply terminals in the reverse direction.

7. The arrangement as claimed in claim 1 in which initiating charge means is connected through a further switch to initially charge the capacitor means to a peak voltage to provide the requisite electrical energy to establish a required current flow in the said coil means.

8. The arrangement as claimed in claim 1 in which there is provided a switched parallel path accross the bridge to maintain a substantially constant value of current through the current supply terminals irrespective of the settings of the switches in the bridge configuration.

9. The arrangement as claimed in claim 1 in which the two arms of the bridge at one end thereof are connected to respective current supply terminals each at different voltage levels to enable different values of current flow to be established through the coil means in respective opposite directions.

10. The arrangement as claimed in claim 9 in which separate series connections each of a capacitor means and a switch are connected to said respective current supply terminals.

11. The arrangement as claimed in claim 1 in which further coil means is provided together with further switch means to enable energy stored in said capacitor means

to be transferred to said further coil means.

12. The arrangement as claimed in claim 11 in which said further switch means also enables energy stored in said further coil means to be transferred to said capacitor means.

13. The arrangement as claimed in claim 12 in which the further switch means is connected in a bridge configuration and said further coil means is connected across the said further bridge configuration.